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MEASUREMENT OF ACOUSTICAL IMPEDANCES OF FLUIDS BY ANALYSIS OF TRANSIENT ACOUSTIC WAVE-SHAPES USING AN ACOUSTICAL WAVEGUIDE WITH PIEZOELECTRIC TRANSDUCERS

JAMES EDWARD SHEEHAN

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MEASUREMENT OF ACOUSTICAL IMPEDANCES OF FLUIDS BY ANALYSIS OF TRANSIENT ACOUSTIC WAVESHAPES USING AN ACOUSTICAL WAVEGUIDE WITH PIEZOELECTRIC TRANSDUCERS.

by

James Edward Sheehan

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NO FORN

Submitted in partial fulfillment

for the degree of

MASTER OF SCIENCE IN PHYSICS

from the

UNITED STATES NAVAL POSTGRADUATE SCHOOL

May 1966

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1966
SHEEHAN, J.

ABSTRACT

A method has been developed for measuring the acoustic impedance of fluids in a fluid-filled waveguide terminated at each end by piezoelectric crystals. Output voltage waveforms were computed for the general case of an arbitrary driving voltage. Analysis of these output waveforms, when the driving voltage was an impulse function, indicated significant changes in the voltage envelopes as the acoustic impedance of the fluid within the waveguide was varied. The time of the first and second phase changes in the second received echo were plotted as a function of fluid impedance. Test fluids were analyzed with an impedance range of from 0.66×10^6 rayls to 19.7×10^6 rayls. The experimental results using the time of the second axis crossing or phase change as the test criterion, indicated that the acoustic impedance can be measured with the following accuracies:

a. 0.5 percent in the neighborhood of $Z = 0.66 \times 10^6$ rayls.

b. 0.9 percent in the neighborhood of $Z = 1.50 \times 10^6$ rayls.

c. 2.0 percent in the neighborhood of $Z = 2.50 \times 10^6$ rayls.

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1. Introduction.

A fluid-filled waveguide, terminated at each end by a piezoelectric transducer, and excited with acoustic transients, was examined as a means of measuring the specific acoustic resistance of the test fluid. When the transmitting crystal is activated by a narrow rectangular pulse, the resultant output voltage pulse shapes are strongly dependent upon the specific acoustic resistance, ρc , of the fluid that fills the guide. By recording the pertinent characteristics of the output waveforms for many fluids of widely varying acoustic impedance, it is possible to determine the value of ρc for an unknown fluid.

If the waveguide were used in conjunction with pressure and temperature measuring devices, measurements of the salinity of sea water at depth in the oceans would be possible. Since the present method for determining salinity of sea water is first to withdraw a sample and then to test it chemically, the advantages of this suggested method are obvious.

Expressions for the output voltage waveforms at the receiving crystal, when the transmitting crystal is driven by an arbitrary voltage, are developed in Sections 2 and 3. These expressions are valid for any fluid and are compared with experimental results for fluids whose acoustic impedances range from 0.66×10^6 rayls to 19.7×10^6 rayls in Section 5. The results are analyzed and a means for measuring acoustic impedance with an accuracy of better than 1.0 percent is shown in Section 7.

2. Theory.

The theory that was developed here is similar to some previous

work done by Redwood[1], Cook[2], Huntington[3], and Coppens[4], among others. Redwood's treatment of the acoustical delay line as a transmission line led to equivalent circuits which are only approximate electrical analogs for the plate transducer. Cook used Laplace transforms and obtained the equivalent mechanical analog for piezoelectric transducers. Huntington also devised an equivalent electrical circuit for piezoelectric transducers. The theoretical development presented here parallels the approach used by Coppens. Whereas Coppens was concerned primarily with the velocity propogation from a vacuum-backed crystal, this theory is concerned with pressures generated and received by crystals with media of arbitrary impedances on both sides of the crystals.

The general equations relating stress and voltage for a piezoelectric crystal will be used to develop expressions for the pressure output of a transmitting crystal, and the voltage output of another crystal receiving the resulting pressure wave. In addition, expressions for the successively reflected pressure packets will be obtained which will enable one to derive expressions for successive output voltage functions. These expressions were obtained for an x-cut quartz crystal, operating in a thickness mode of vibration, with an arbitrary voltage V(t) applied. It will be assumed that losses in the crystal and loading medium may be neglected, and that the thickness mode is the only mode appreciably excited, so that only displacements in the X-direction are of significance.

The basic equations for piezoelectric action with the above assumptions are[3]

$$V(t) = h\{\xi(d,t) - \xi(0,t)\} + \sigma(t)\frac{4\pi d}{\epsilon} \qquad (1)$$

$$S(x) = \rho c^2 \frac{\partial \xi}{\partial x} + h\,\sigma(t) \qquad (2)$$

where the defining terms in the above equation are as follows.

V(t) = applied voltage

h = appropriate piezoelectric stress constant

ξ = particle displacement

$\sigma(t)$ = free surface charge density

d = thickness of the crystal

ϵ = dielectric constant of the crystal

S(x) = stress

ρ = density of the crystal

c = velocity of sound in the crystal

It has been shown [4] that for quartz acting as a transmitter,

$$h\{\xi(d,t) - \xi(0,t)\} << \frac{\sigma(t)\,4\pi d}{\epsilon}.$$

Equation 1 than becomes

$$V(t) = \sigma(t)\frac{4\pi d}{\epsilon}. \qquad (3)$$

Solving Eq. 3 for $\sigma(t)$ and letting

$$a = \frac{\epsilon d}{4\pi d}, \qquad (4)$$

Eq. 2 can be expressed as

$$S(x) = \rho c^2 \frac{\partial \xi}{\partial x} + a\,V(t). \qquad (5)$$

If ξ^+ represents a wave traveling the +x direction and ξ^- a wave traveling in the -x direction, then

$$c \frac{\partial \xi}{\partial x} = \mp \frac{\partial \xi}{\partial t}^{\pm} \tag{6}$$

from the wave equation, $\frac{\partial^2 \xi}{\partial t^2} = c^2 \frac{\partial^2 \xi}{\partial x^2}$.

Use of the following notation:

MEDIUM 1	CRYSTAL	MEDIUM 2
$Z_1 = \rho_1 c_1$	$Z = \rho c$	$Z_2 = \rho_2 c_2$
$M_1 = \frac{Z_1}{Z}$		$M_2 = \frac{Z_2}{Z}$ (7)
$\xi_1 = \xi_1^+ + \xi_1^-$	$\xi = \xi^+ + \xi^-$	$\xi_2 = \xi_2^+ + \xi_2^-$

and the boundary conditions of continuity of displacement,

$$\xi_1(0,t) = \xi(0,t), \tag{8-a}$$

$$\xi(d,t) = \xi_2(d,t), \tag{8-b}$$

and continuity of stress,

$$S_1(0) = S(0), \tag{8-c}$$

$$S_2(d) = S(d), \tag{8-d}$$

together with Eqs. 5 and 6 results in

$$Z_1 \frac{\partial}{\partial t}\left\{\xi_1^+(0,t) - \xi_1^-(0,t)\right\} = Z \frac{\partial}{\partial t}\left\{\xi^+(0,t) - \xi^-(0,t)\right\} - a V(t) \tag{9-a}$$

and

$$Z_2 \frac{\partial}{\partial t}\left\{\xi_2^+(d,t) - \xi_2^-(d,t)\right\} = Z \frac{\partial}{\partial t}\left\{\xi^+(d,t) - \xi^-(d,t)\right\} - a V(t) \tag{9-b}$$

By addition and subtraction of Eqs. 9-a and 9-b, and the use of the relationship $p = Z\frac{\partial \varepsilon}{\partial t}$, the following pressure relationships are obtained:

$$p^-(0,t) = \frac{M_1}{1+M_1}\, a\, V(t), \qquad (10\text{-a})$$

$$p^+(0,t) = -\frac{1}{1+M_1}\, a\, V(t), \qquad (10\text{-b})$$

$$p^-(d,t) = -\frac{1}{1+M_2}\, a\, V(t), \qquad (10\text{-c})$$

and

$$p^+(d,t) = \frac{M_2}{1+M_2}\, a\, V(t). \qquad (10\text{-d})$$

If one uses the following definitions,

$$V(i) = V(t - 2d/c),$$

$$p(i) = p(t - 2d/c),$$

$$R(j) = \frac{Z_j - Z}{Z_j + Z} = \frac{M_j - 1}{M_j + 1}, \qquad \text{(pressure reflection coefficient)}$$

$$T(j) = \frac{2Z_j}{Z_j + Z} = \frac{2M_j}{M_j + 1}, \qquad \text{(pressure transmission coefficient)}$$

where j indicates either surface 1 (X=0) or 2 (X=d) and i is an integer, then Eqs. 10-a through 10-d become

$$p^-(0,t) = p^-(0,t), \qquad (11\text{-a})$$

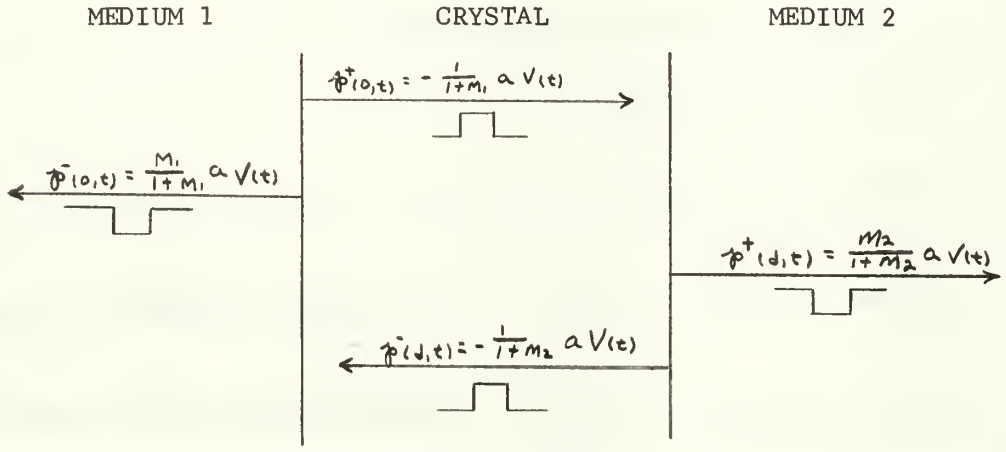
$$p^+(0,t) = -\frac{1}{M_1}\, p^-(0,t), \qquad (11\text{-b})$$

$$p^-(d,t) = -\frac{1}{M_2}\,\frac{T_2}{T_1}\, p^-(0,t), \qquad (11\text{-c})$$

and

$$p^+(d,t) = \frac{T_2}{T_1}\, p^-(0,t). \qquad (11\text{-d})$$

According to this analysis, when a voltage function is impressed across the crystal transmitter, each face of the crystal acts like a pressure generating device and sends a pressure wave into both the crystal and the adjacent medium. The magnitude of each of the four pressure waves is determined by the acoustic impedances of the two media at the relevant boundary. It should be noted that the pulses sent into the crystal are of like phase; they are, however, of opposite phase to those sent into the surrounding media. This is indicated in the following diagram.



PRESSURE PATTERNS

Figure 1 is a graphical development of the growth of a pressure waveform resulting from a single voltage impulse impressed on the crystal. At time zero, four pulses are generated. From surface 1, $\mathcal{P}^-(0,t)$ is sent into medium 1 and $-\frac{1}{M_1}\mathcal{P}^-(0,t)$ is sent into the crystal. From surface 2, $\frac{T_2}{T_1}\mathcal{P}^-(0,t)$ is sent into medium 2 and $-\frac{1}{M_1}\frac{T_2}{T_1}\mathcal{P}^-(0,t)$ is sent into the crystal. As time increases, each of the two pulses sent into the crystal is repeatedly reflected between the faces of the crystal. At each reflection, some energy is transmitted into the adjacent medium.

Figure 1. Growth of Pressure Patterns.

After a time d/c, the wave which started at surface 2 is partially reflected at surface 1 and the portion transmitted into medium 1 is $T_1\left\{-\frac{1}{M_2}\frac{T_2}{T_1}\bar{p}(0,t)\right\}$. After a time 2 d/c, the wave which started at surface 1 has been reflected by surface 2 and is now at surface 1. The portion now transmitted into medium 1 is $T_1R_2\left\{-\frac{1}{M_2}\bar{p}(0,t)\right\}$; that transmitted into medium 1 at time 3 d/c is $T_1R_1R_2\left\{-\frac{1}{M_2}\frac{T_2}{T_1}\bar{p}(0,t)\right\}$. The resultant waveform sent into medium 1 is therefore, a series of impulses of varying amplitude and phase, each separated in time by d/c, the time of flight of sound in the crystal. This series can be expressed as

$$\bar{p}_1^0(0,t) = \frac{M_1}{1+M_1}\,a\,V(0) + T_1\left\{-\sum_{\lambda=0}^{\infty}\frac{1}{1+M_2}\,a\,V(\lambda+\tfrac{1}{2})(R_1R_2)^{\lambda}\right.$$

$$\left.-\sum_{\lambda=1}^{\infty}\frac{1}{1+M_1}\,a\,V(\lambda)\,\frac{(R_1R_2)^{\lambda}}{R_1}\right\}. \qquad (12)$$

In the above equation, the subscript for the pressure indicates the crystal at which the pressure acts. The receiving crystal is numbered 1 and the generating crystal numbered 2. The superscript indicates the number of times the entire packet has been reflected. As a further example, $\bar{p}_1^2$ is the pressure at the receiving crystal (numbered 1) which has been reflected twice, once from the receiving crystal and again from the transmitting crystal so that it is detected at the receiver after three trips through the test fluid. The same notation will be used for the generated voltages: E_1^0 is the voltage generated at the receiving crystal from the initial pressure packet p_1^0 , E_1^2 is the voltage generated at the receiver due to p_1^2 , the third generated voltage is E_1^4 , etc.

Equation 12 is in agreement with Eq. 11 of Cook [2] as used in his Fig. 4, and with Eq. 7.11 of Coppens [4] when the appropriate simplifications are made for vacuum backing.

Employment of the same technique as represented in Fig. 1 to derive the expression for p_1' , yields

$$p_1' = -R_1 p_{1(0)}^{\circ} + \sum_{\lambda=0}^{\infty} \frac{1}{M_1} T_1^2 \frac{(R_1R_2)^{\lambda}}{R_1} p_1^{\circ}(\lambda) \Big) \qquad (13)$$

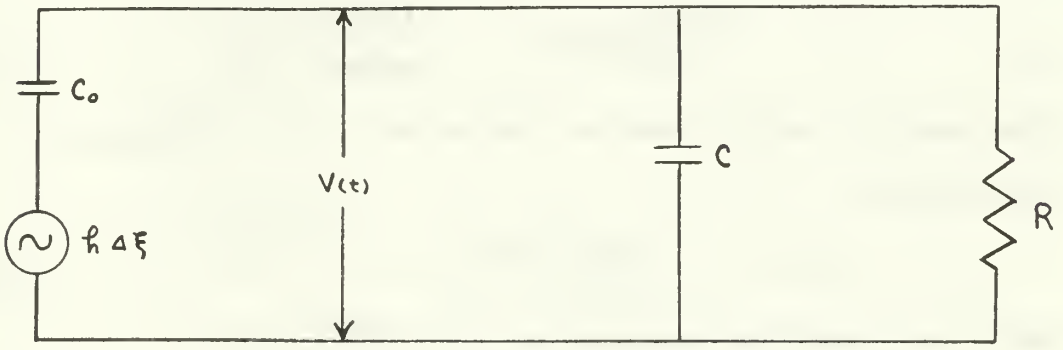
and therefore

$$\partial_t \left\{ \xi_{(d,t)} - \xi_{(0,t)} \right\} = -\frac{1}{2M_1} T_1 \left\{ p_{1(0)}^{\circ} - \sum_{\lambda=0}^{\infty} \frac{T_2}{M_2} (R_1R_2)^{\lambda} p_1^{\circ}(\lambda+\tfrac{1}{2}) \right.$$

$$\left. - \sum_{\lambda=1}^{\infty} \frac{T_1}{M_1} \frac{(R_1R_2)^{\lambda}}{R_1} p_1^{\circ}(\lambda) \right\} \qquad (14)$$

Equation 14 was derived using the expression $p = Z\frac{\partial \xi}{\partial t}$ and will be necessary in solving for the output voltage E_1° .

If we consider the external load of the receiving crystal to be a coaxial cable and voltage amplifier, the equivalent circuit and the defining terms of the crystal and load are as shown below:



where Co = $\frac{A\epsilon}{4\pi d}$ the capacitance of the crystal

A = the electrode area of the crystal

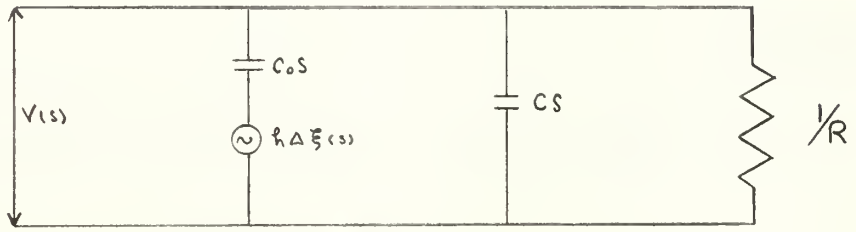
C = external shunt capacitance

R = external circuit resistance

$\Delta\xi = \xi_{(d,t)} - \xi_{(0,t)}$

$\Delta\dot{\xi} = \frac{\partial}{\partial t}\left\{ \xi_{(d,t)} - \xi_{(0,t)} \right\}$.

To derive the voltage response of the equivalent circuit using Laplace transforms, consider the transformed admittance network with all initial conditions zero.[5]



Solving for the currents into the upper node yields the equation

$$(V(s) - h\Delta\xi(s))\,S C_0 + V(s)\,CS + \frac{V(s)}{R} = 0. \qquad (15)$$

By denoting the displacement transfer function as

$$H(s) = \frac{V(s)}{\Delta\xi(s)}\,, \qquad (16)$$

Eq. 15 can be solved with the result

$$H(s) = \frac{hRC_0 S}{1 + R(C_0+C)S} = \frac{hRC_0 S / R(C_0+C)}{\frac{1}{R(C_0+C)} + S} \qquad (17)$$

The velocity transfer function, defined as $H'(s) = \frac{V(s)}{\Delta\dot{\xi}(s)}$, is therefore

$$H'(s) = \frac{hRC_0 / R(C_0+C)}{\frac{1}{R(C_0+C)} + S}\,, \qquad (18)$$

which for simplicity is written as

$$H'(s) = \frac{A}{S + \frac{1}{B}}\,, \qquad (19)$$

with $A = \frac{hRC_0}{B}$ and $B = R(C_0+C)$.

The output of the transformed network is

$$G(s) = F(s)\,H'(s)\,, \qquad (20)$$

Where $F(s)$ is the transform of the input to the equivalent circuit

$$\Delta\dot{\xi}(t) = f(t) \qquad (21)$$

When $f_{(t)}$ is a rectangular pulse of height a, and duration λ, $f_{(t)}$ can be expressed as

$$f_{(t)} = a\,1_{(t)} - a\,1_{(t-\lambda)} . \tag{22}$$

$F_{(s)}$ is the Laplace transform of Eq. 20 so that

$$F_{(s)} = \frac{1}{s} - \frac{1}{s} e^{-\lambda s} \tag{23}$$

Substituting Eqs. 19 and 23 into Eq. 20 yields

$$G_{(s)} = \frac{aA}{s(s+\frac{1}{B})} (1 - e^{-\lambda s}) \tag{24}$$

or

$$G_{(s)} = \frac{a\,h\,RC_0 / R(C_0+C)}{s\left(s + \frac{1}{R(C_0+C)}\right)} (1 - e^{-\lambda s}) \tag{25}$$

When $G_{(s)}$ is transformed back into the time domain, the output voltage is obtained:

$$v_{(t)} = g_{(t)} = a\,h\,RC_0 \left(1 - e^{-t/R(C_0+C)}\right)\left(1_{(t)} - 1_{(t-\lambda)}\right), \tag{26}$$

or

$$v_{(t)} = h\,RC_0\,\Delta\dot{\xi} \left(1 - e^{-t/R(C_0+C)}\right). \tag{27}$$

If we assume that

$$\frac{t}{R(C_0+C)} \gg 1 , \tag{28}$$

then

$$v_{(t)} = h\,RC_0\,\Delta\dot{\xi} . \tag{29}$$

Equation 29 says that for the case in question, $\Delta\dot{\xi}$ being a rectangular pulse and $R(C_0+C) \ll 1$, the output voltage across the external load is directly proportional to the pressure waveform $P_{(t)}$. For the experimental work to follow, $R(C_0+C) = 1.6 \times 10^{-8}$ and the assumption of Eq. 28 is justified.

As a test of the validity of Eq. 29, a small amplitude test signal was applied to the circuit and the external resistance R was

varied over a considerable range while noting the relative output voltage $v(t)$. The range of R used was 3 ohms to 1 megohm. The results shown in Fig. 3, show conclusively that the output voltage is indeed proportional to R in the neighborhood of R = 200 ohms, the experimental value of resistance used. The curve appears to saturate in the neighborhood of R = 600 ohms and has a relatively flat response as R is increased further. The relative output voltage rising only from 0.48 at R = 560 ohms to 0.54 at R = 1 megohm.

3. Theoretically Predicted Waveforms

When Eq. 16 is substituted into Eq. 29, we have

$$E_1^0 = -\frac{hRC_0}{Z}\frac{T_1}{M}\left\{\mathcal{P}_1^0(0) - \sum_{i=0}^{\infty}\frac{T_2}{M_2}(R_1R_2)^i\mathcal{P}_1^0(i+1/2) - \sum_{i=1}^{\infty}\frac{T_1}{M_1}\frac{(R_1R_2)^i}{R}\mathcal{P}_1^0(i)\right\}, \tag{30}$$

which is an expression for the voltage developed at the receiving crystal as a result of a pressure packet $\mathcal{P}_1^0(t)$ which is traveling from the transmitter to the receiver (subscript 1) and has not been reflected (superscript 0).

Substitution of Eq. 12 into Eq. 30 yields an expression for the generated output voltage waveform in terms of the applied driving voltage. A digital computer was utilized to compute first the individual pressure waveforms, as in Eq. 12, and then using this to compute the final output voltage waveforms using Eq. 30.

When comparing these results with those of Coppens, it was noted that an error exists in his Eq. 7.23, an expression for the first voltage generated at the receiving crystal. This error originates in his Eq. 7.16, the expression for velocities of the crystal boundaries. His equations have t_2, the amplitude transmission coefficient,

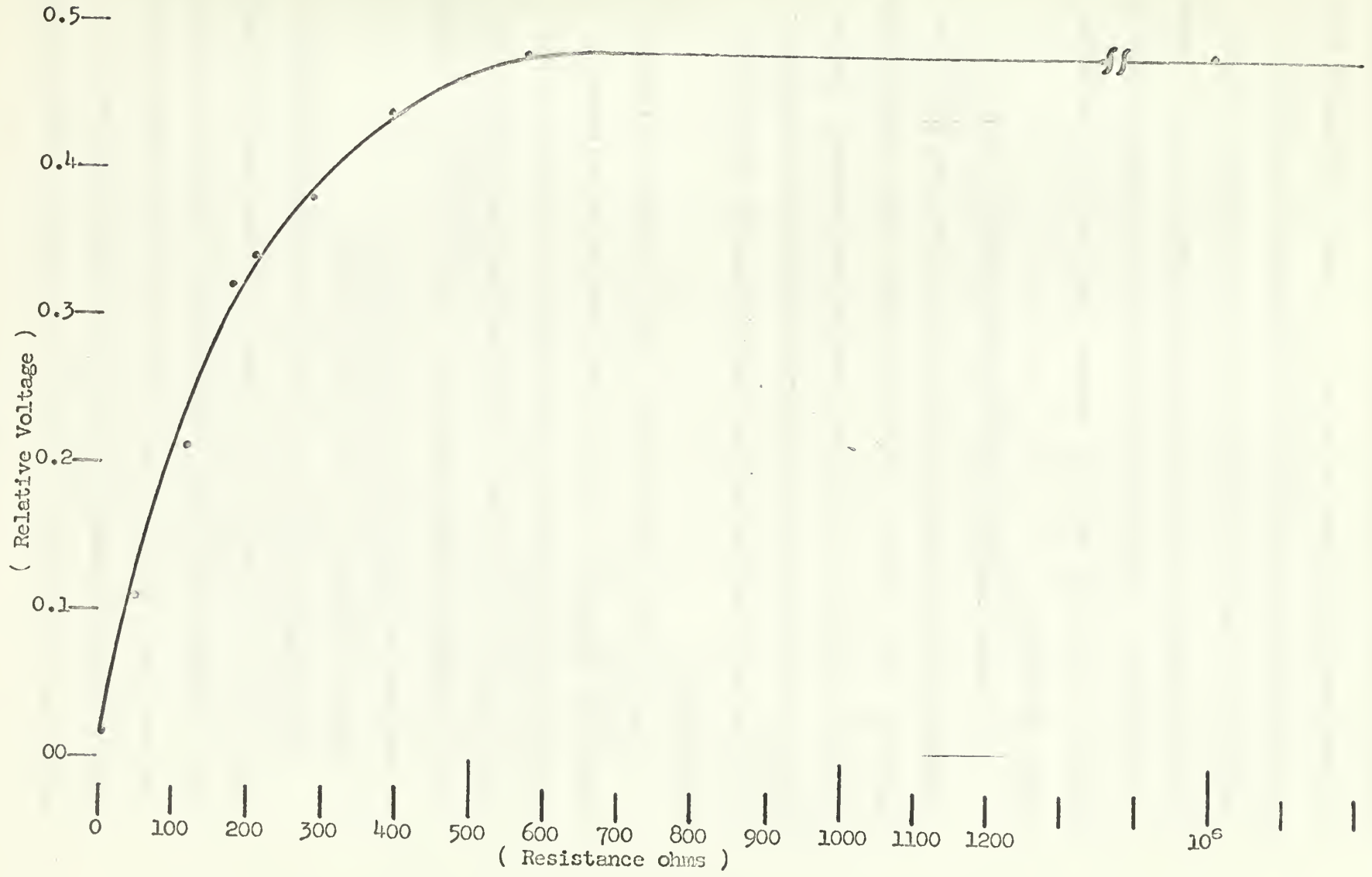


Figure 2. Relative Voltage vs. Resistance.

appearing in both the summation terms. In Eq. 7.23, when he assumes a vacuum backing, t_2 takes the value 2.0. However, the second summation term in Eq. 7.16 should have t_1, the amplitude transmission coefficient at the fluid boundary, vice t_2 and therefore, his Eq. 7.23 should have t_1 vice 2.0 in the second summation term. Although this effect will be negligible for fluids with an acoustic impedance equal to or less than water, it becomes significant for fluids with higher impedances.

In a manner completely similar to that described by Fig. 1, expressions for the successive reflected pressure waves within the cavity, $\mathcal{P}_i^1$, $\mathcal{P}_i^2$, $\mathcal{P}_i^3$, etc., can be obtained. Each of these pressure waves will generate a voltage as it strikes this crystal. The expressions for the succeeding generated voltages can be obtained by utilizing Eq. 30 with appropriate substitutions for the pressure expression $\mathcal{P}_i^0$.

Using a C.D.C. digital computer 1604, the first 13 pressure packets, $\mathcal{P}_i^0$ through $\mathcal{P}_i^{13}$, and the first seven output voltages E_i^0 through E_i^{12} were computed for various fluids. In addition, these output voltage waveforms were plotted and their amplitudes tabulated. The computer program presented in Appendix I is quite flexible and self-explanatory.

4. Design of Apparatus and Associated Equipment

The propogation of sound occurs in the acoustical delay line, shown in Fig. 3, between two 5 mc quartz crystals, spaced 2.0 inches apart in a test cavity of 1.0 inch diameter. The ends of the stainless steel walls that are flush with the plate transducers were constructed with great care to ensure that the faces were parallel to within one one-thousandth of an inch. The acoustic distance for one

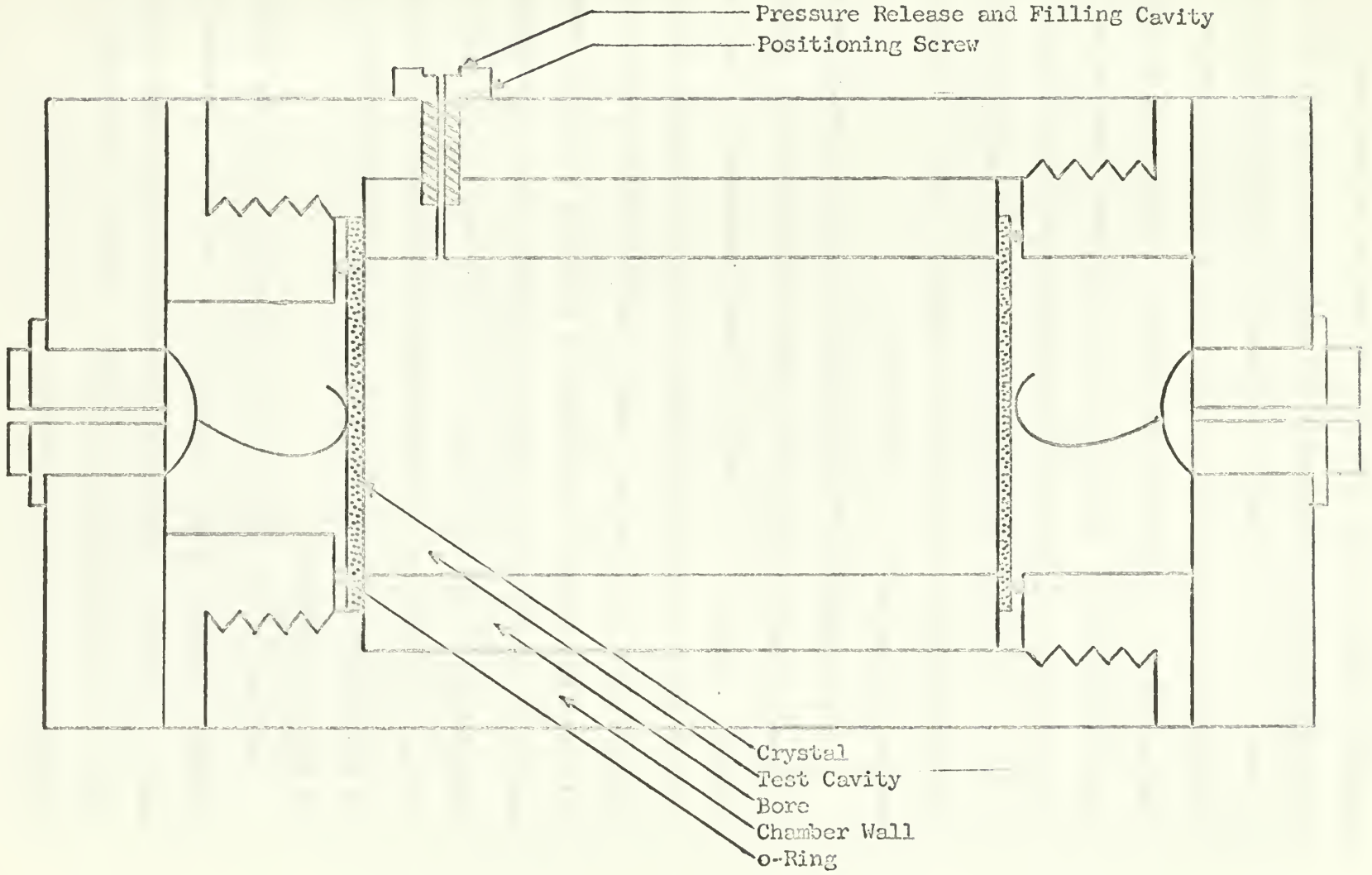


Figure 3. Cutaway Drawing of Acoustical Waveguide.

way transmission is therefore taken to be the distance between the crystals. Rubber O-rings were used to provide an even circular strain on the crystals and vacuum grease was used on the edges of the crystals to ensure liquid tight seals. Low tension spring electrical connectors were used for the electrical contact to the gold plated surface to minimize any force applied to the crystal. Two removable end caps permit easy assembly. The small positioning screw prevents any torsional motion of the bore within the assembly and the filling hold provides a simple way of eliminating air from the cavity and ensuring that fluid completely fills the test chamber, as well as providing a pressure release outlet from the cavity.

A block diagram of the associated electrical equipment necessary for detecting and monitoring the output voltage waveforms is shown in Fig. 4. Table I is a listing of these components by type. The 1.5 volt battery and voltage divider provide a convenient reference voltage on the oscilloscope. When a ten-turn potentiometer was used as the voltage divider it provided the reference voltage of adequate sensitivity necessary for accurate placement in the millivolt range. Determination of the amplitude of any particular pulse within a waveform was accomplished by superimposing the dc reference voltage upon the pulse in question and reading the desired voltage directly from the digital voltmeter.

Although a unit impulse function was desired for the driving voltage, it was, of course, unobtainable. The pulse generator, however, did provide a rectangular pulse of 0.08 microseconds duration, which is less than the time of flight of sound in the crystal of 0.01 microseconds and therefore adequate for this experiment.

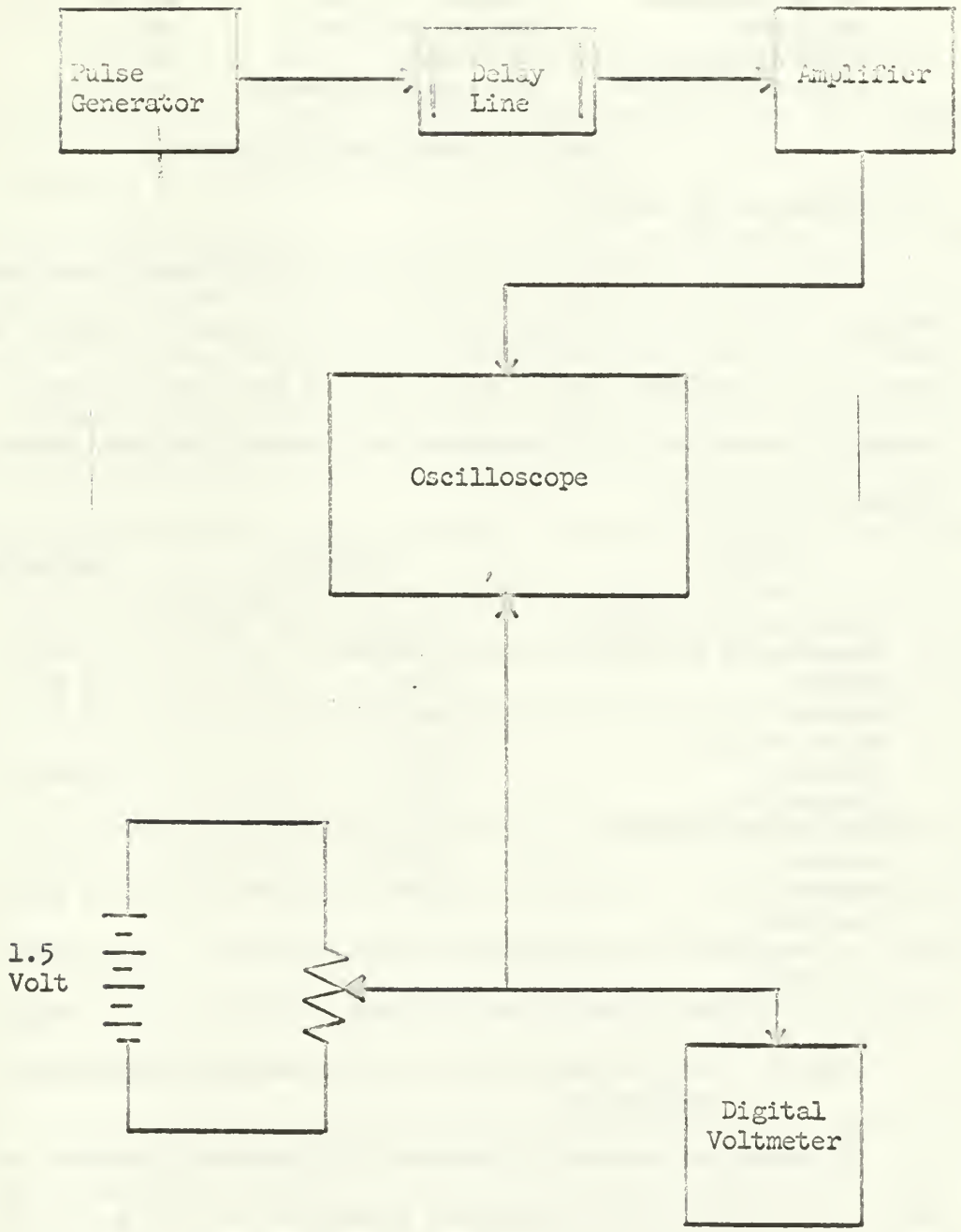


Figure 4. Associated Electrical Equipment.

EQUIPMENT	MANUFACTURER	MODEL
Pulse Generator	DuMont	404 B
Amplifier	Hewlett Packard	460 A
Oscilloscope	Fairchild	766 H
Digital Voltmeter	Electric Instruments	DXA-000

TABLE I. ASSOCIATED EQUIPMENT.

5. Discussion of Results

To test the validity of the theory, distilled water was chosen because it makes an excellent acoustic bond to quartz crystals and because its impedance lies in the region of particular interest. The acoustic impedances of all materials of interest for this report are listed in Table II.

MATERIAL	IMPEDANCE	REFERENCE
Fresh water T = 21°C	1.48231 X 10^6 rayls	6,7
Fresh water T = 25°C	1.49164 "	6,7
Quartz	1.52 "	8
Glycerol	2.50 "	7
Nitro benzine	1.79 "	7
Mercury	19.7 "	9
Turpentine	1.11 "	9
Tert-butyl Chloride	0.827 "	10
Acetone	0.725 "	10
Pentane	0.66 "	8
Sea water T = 25°C, S = 34.0 ppt	1.56738 "	6,11
Sea water T = 25°C, S = 35.0 ppt	1.57084 "	6,11

TABLE II. Various Materials and their Respective Acoustic Impedances.

The water was carefully degassed by alternately heating and applying a vacuum. The temperature stabilized at 21°C prior to testing. The driving voltage $V_{(t)}$ was a rectangular pulse of duration 0.08 microseconds and of amplitude 30 volts.

The first five voltage waveforms E_1° through E_1^8 were photographed and the first two, E_1° and E_1^4, were carefully analyzed for the amplitude of each individual pulse within the waveform. Values

for these individual pulse amplitudes for E_1^0 are listed in Appendix II, and for E_1^8 in Appendix III.

With the help of the computer program previously mentioned, theoretical output voltages were computed and graphed. The computed amplitudes of the individual pulses within E_1^0 and E_1^a are also listed in Appendices II and III. It should be noted that these computed amplitudes do not include the constant $\beta RC_0 a/\rho c$ from Eqs. 12 and 30, and are computed for a driving voltage given by an impulse function of unit height. In addition, the measured voltages listed were corrected for the constant amplification factor caused by the wide band amplifier. The calculated voltages do include the correction for the amplitude of the driving voltage which was 30.0 volts vice 1.0 volt. The columns in Appendices II and III labeled "Calculated Voltages and Measured Voltages" should therefore be used for comparison.

The computed voltages E_1^0 through E_1^8 for distilled water are shown in Figs. 5 through 9. The photographs of the actual voltage waveforms E_1^0 through E_1^8 are shown in Figs. 10 through 14. These figures show that there is excellent agreement between theory and measurement.

For comparison, Fig. 15 is a plot of the envelopes of the actual and calculated voltages for the first received output, E_1^0. The solid curve represents the calculated envelope and the dots represent actual measured pulses. Fig. 16 is the same plotted data for the second received output E_1^a. Since the relative shapes of the waveform are of particular interest, rather than the absolute amplitudes, the actual values have been normalized so that the maximum positive voltages, measured and calculated, coincide.

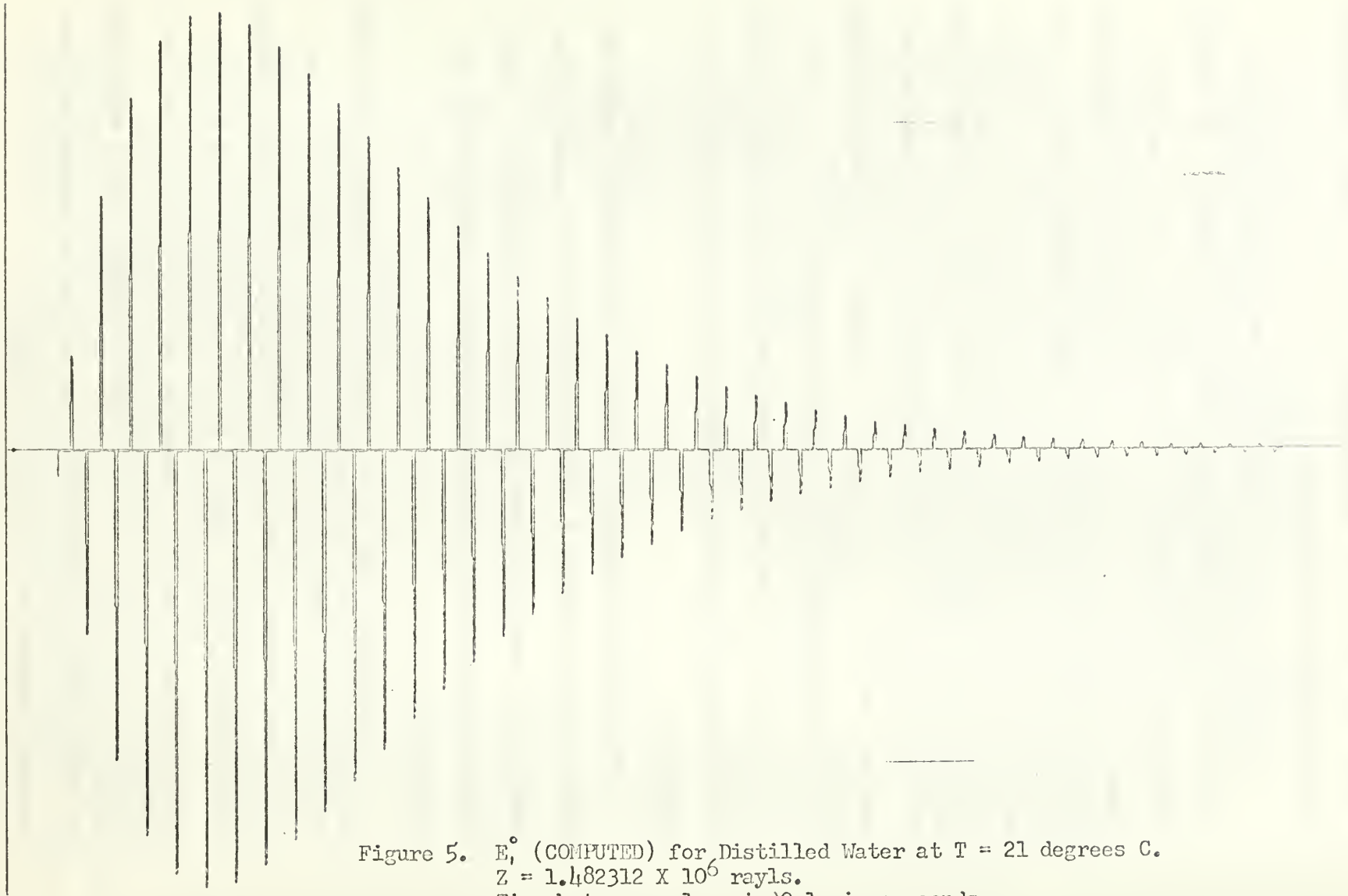


Figure 5. E_1° (COMPUTED) for Distilled Water at T = 21 degrees C.
Z = 1.482312×10^6 rayls.
Time between pulses is 0.1 microseconds.

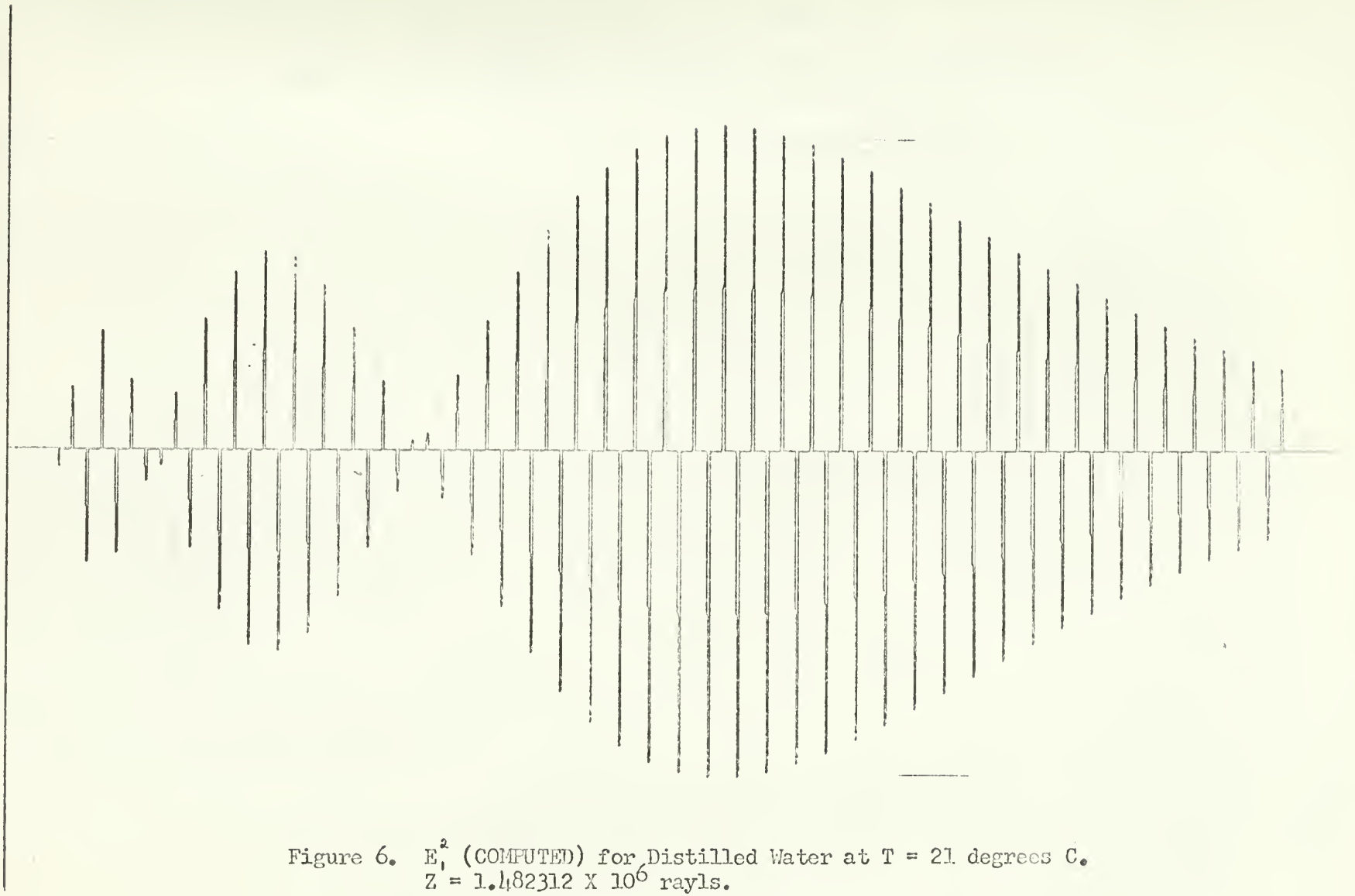


Figure 6. E_1^2 (COMPUTED) for Distilled Water at T = 21 degrees C.
Z = 1.482312 X 10^6 rayls.
Time between pulses is 0.1 microseconds.

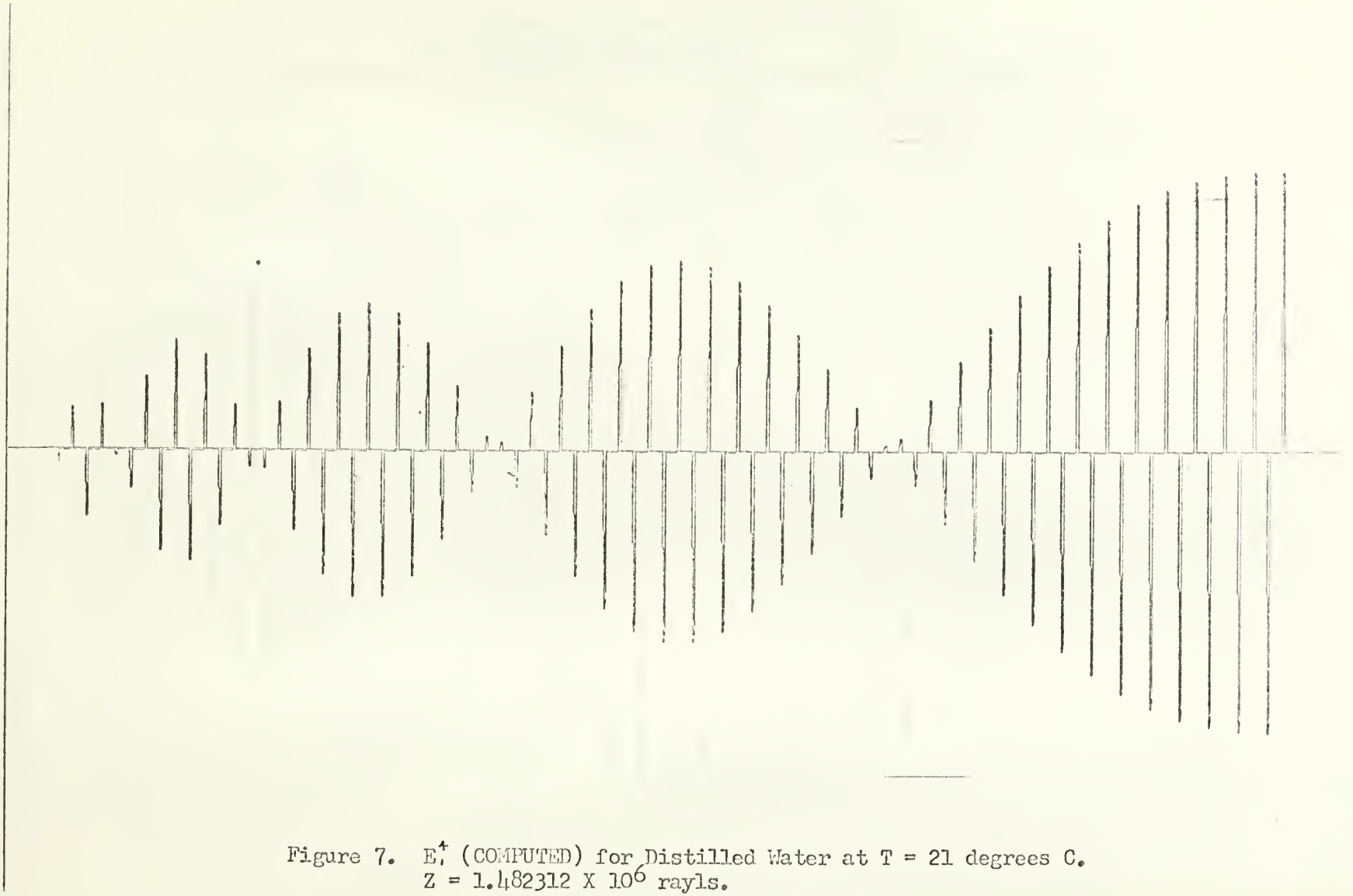


Figure 7. E_1^4 (COMPUTED) for Distilled Water at T = 21 degrees C.
Z = 1.482312×10^6 rayls.
Time between pulses is 0.1 microseconds.

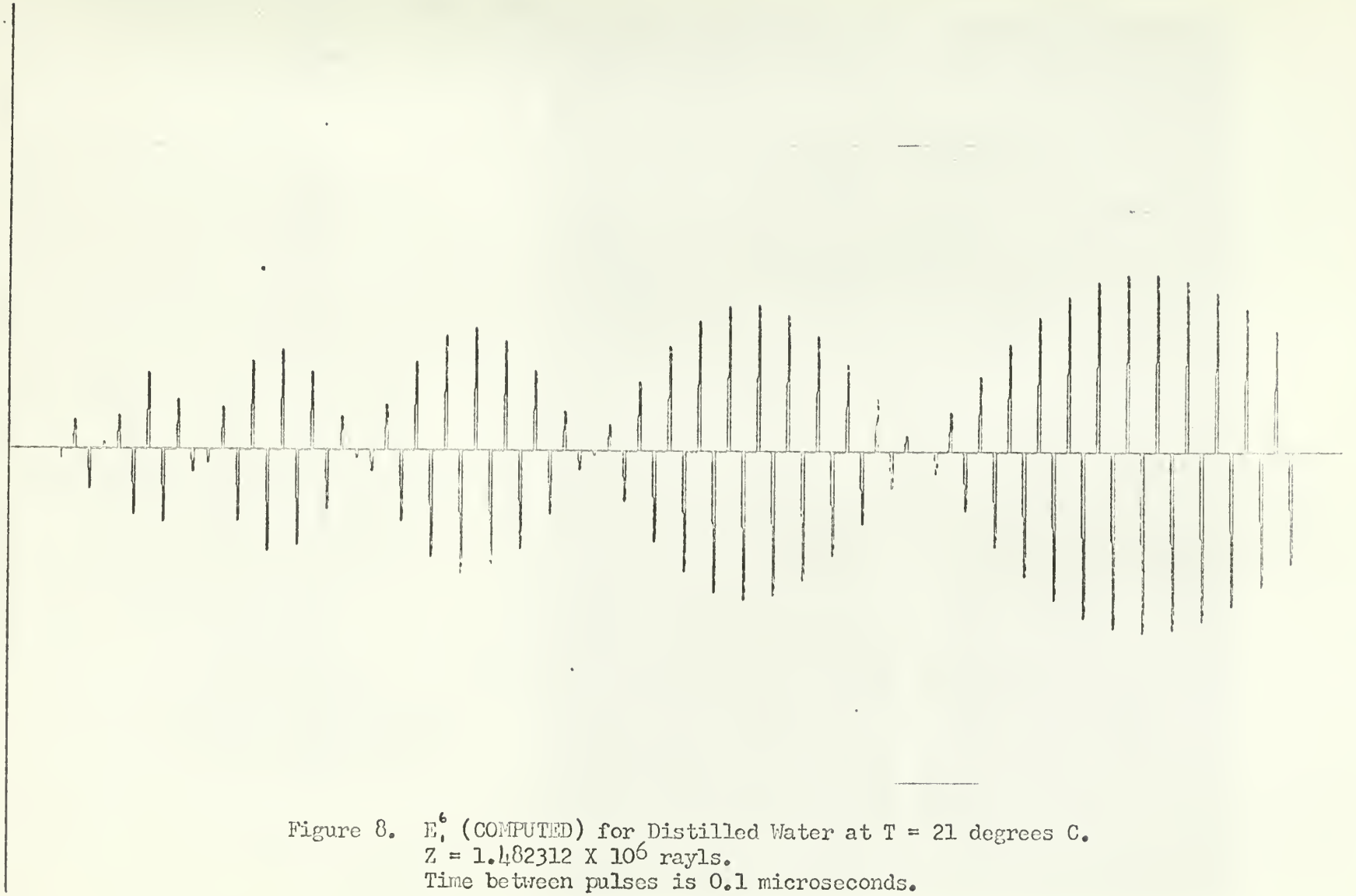


Figure 8. E_1^6 (COMPUTED) for Distilled Water at T = 21 degrees C.
Z = 1.482312 X 10^6 rayls.
Time between pulses is 0.1 microseconds.

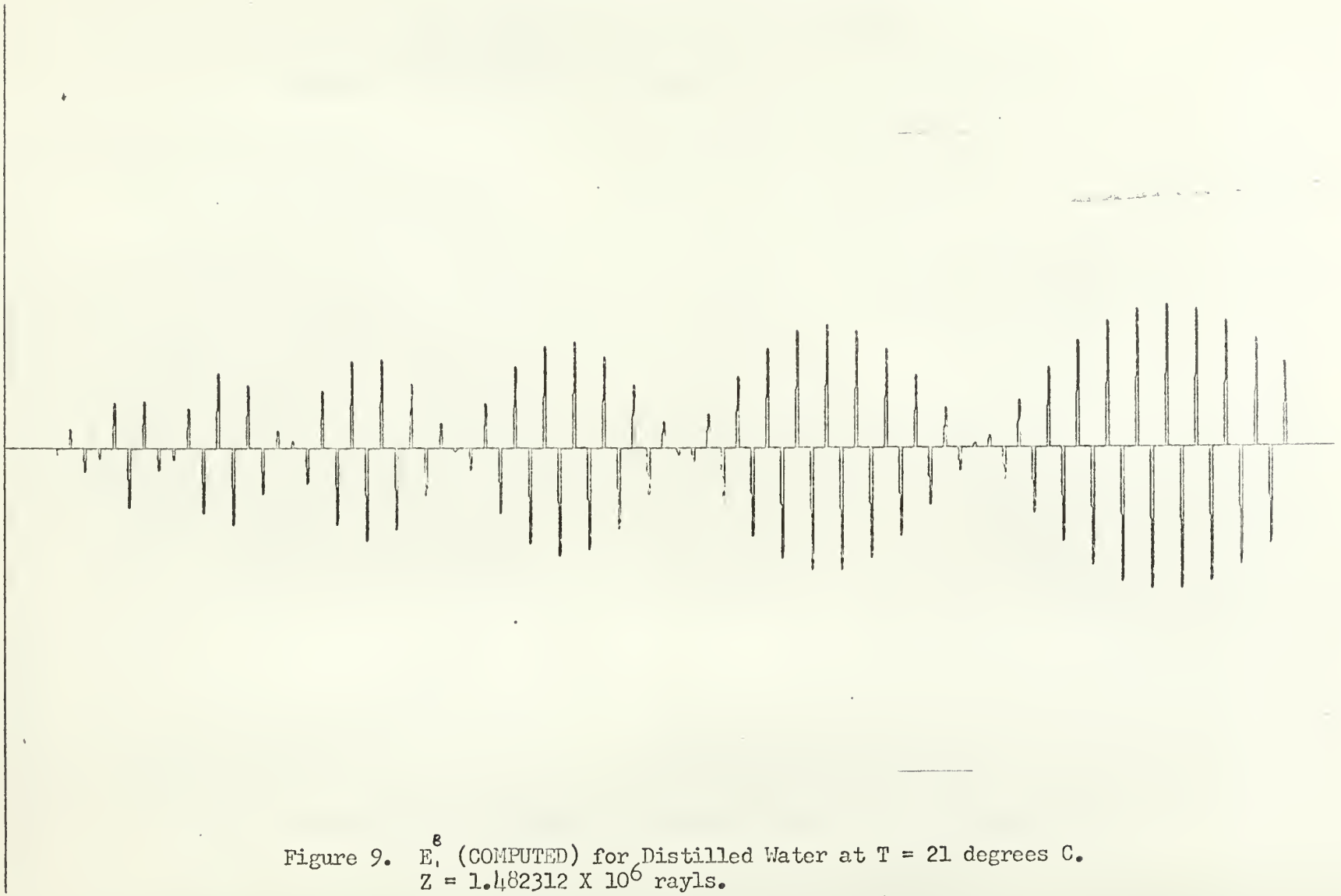


Figure 9. E_1^8 (COMPUTED) for Distilled Water at T = 21 degrees C.
Z = 1.482312 X 10^6 rayls.
Time between pulses is 0.1 microseconds.

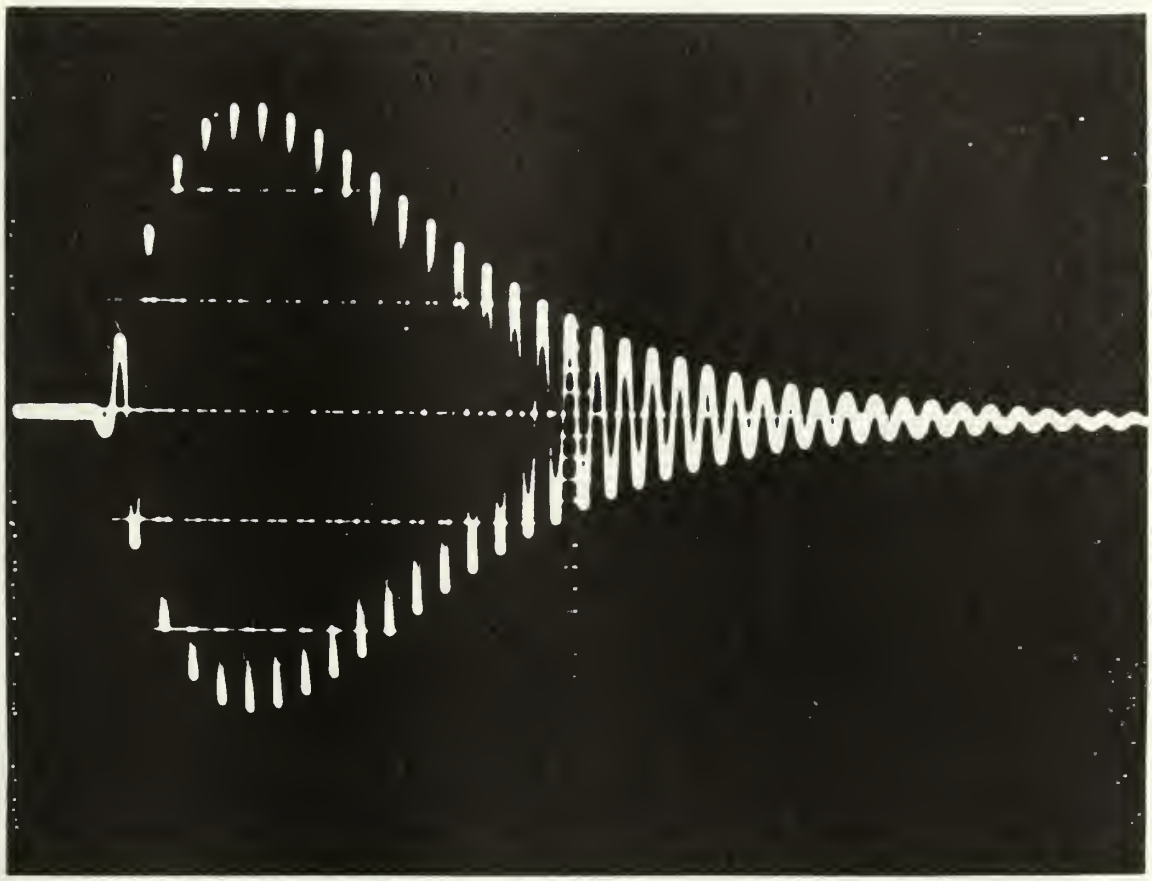


Figure 10. Photograph of the waveform E_1^o for distilled water at T=21 degrees C.

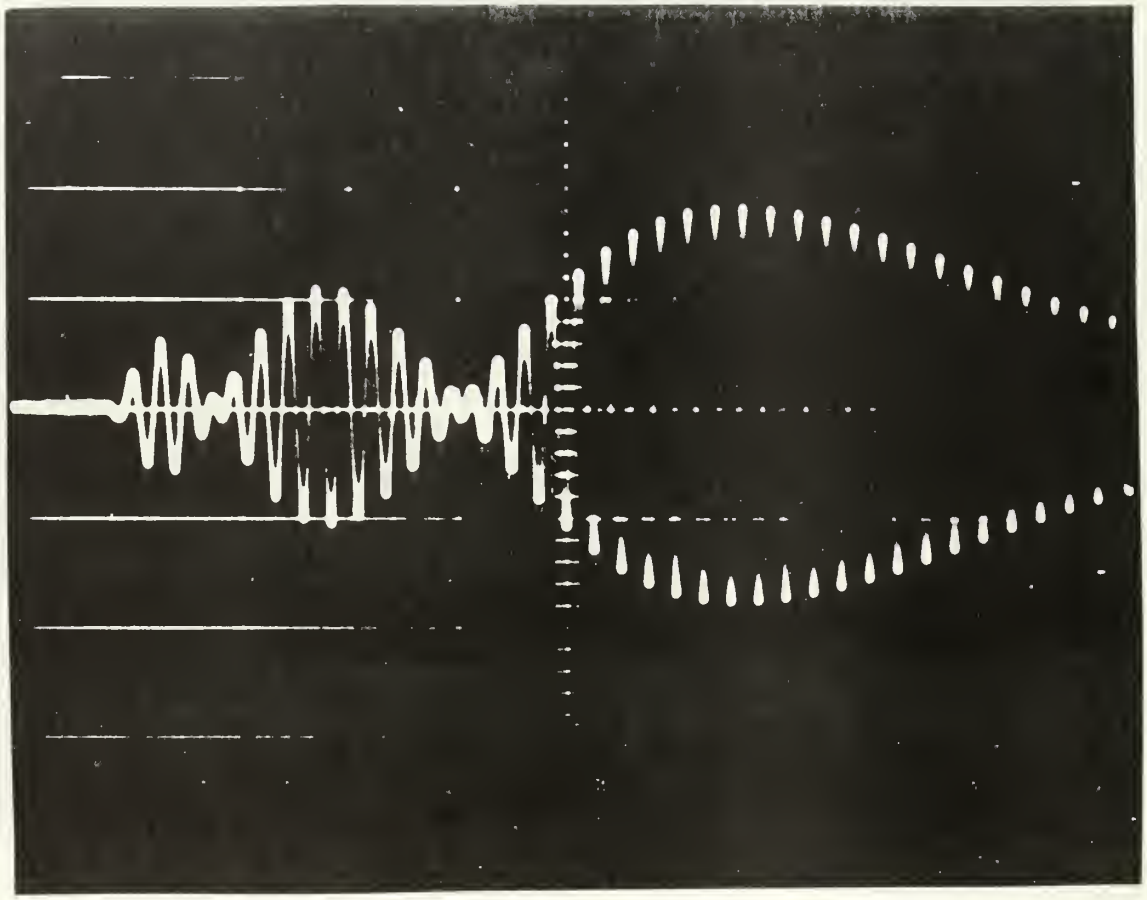


Figure 11. Photograph of the waveform $A_1^{\prime\prime}$ for distilled water at T=21 degrees C.

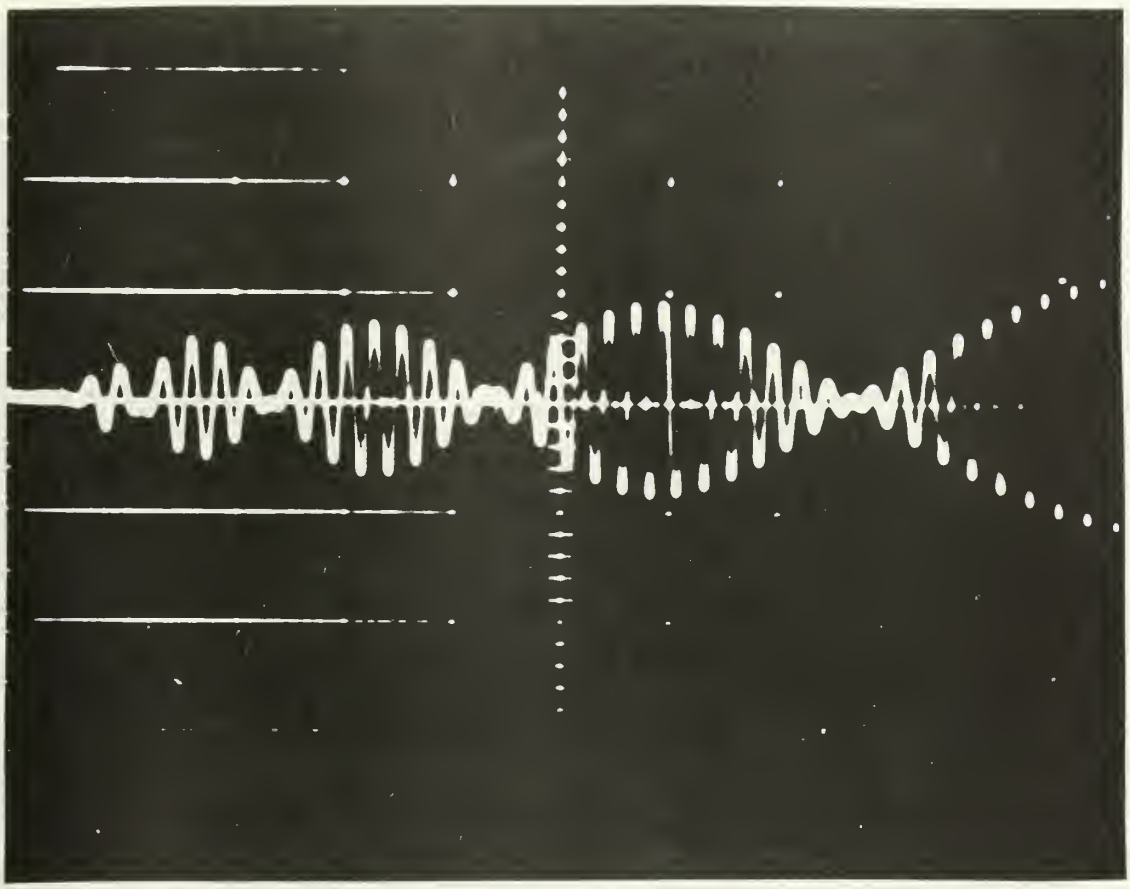


Figure 12. Photograph of the waveform E_1^4 for distilled water at T=21 degrees C.

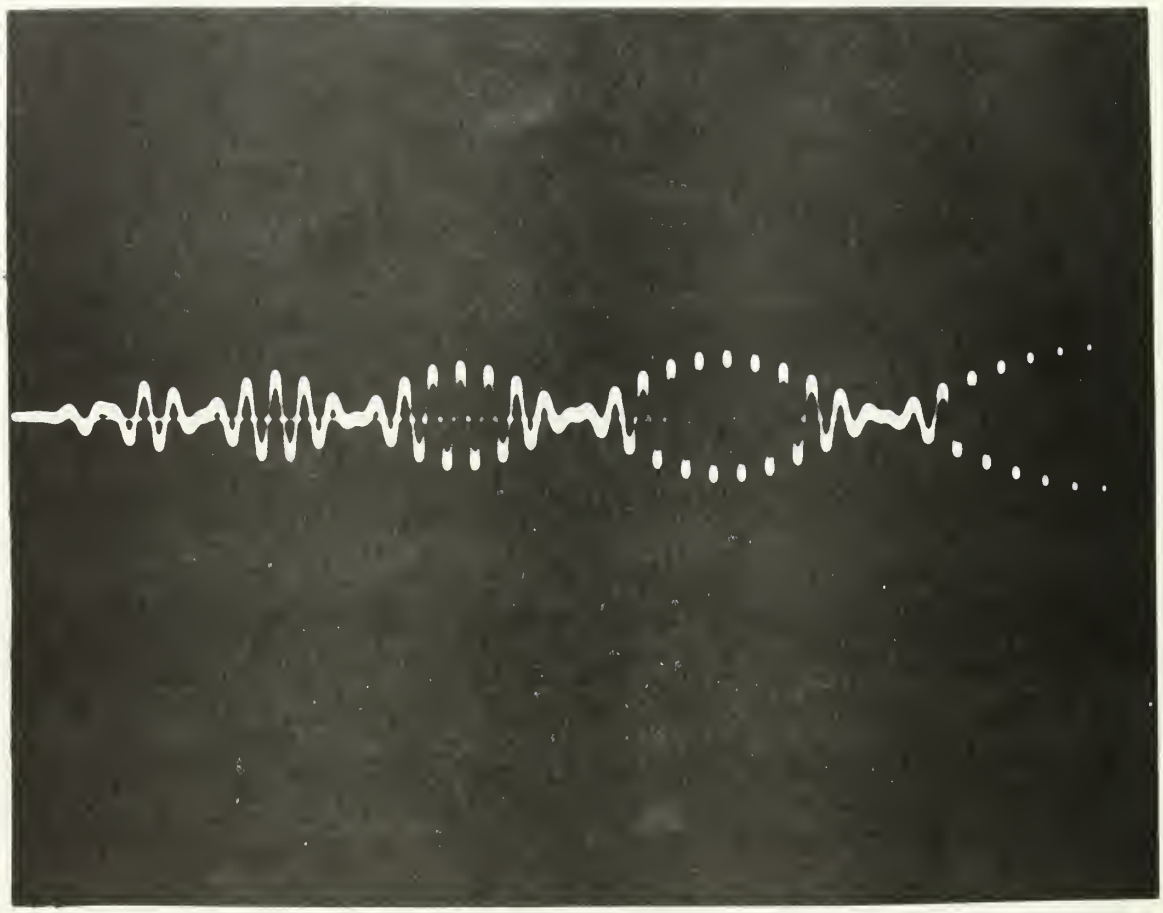


Figure 13. Photograph of the waveform E_1^6 for distilled water at T=21 degrees C.

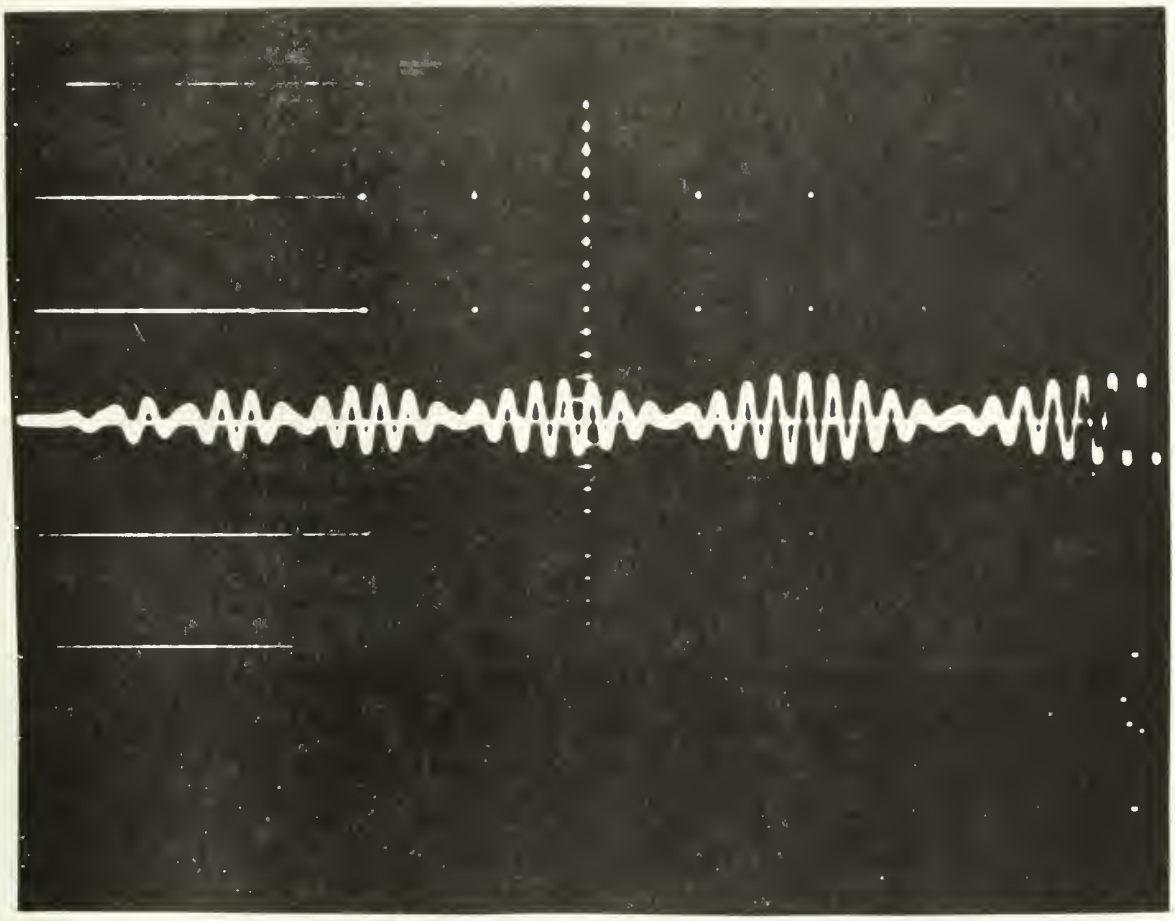


Figure 14. Photograph of the waveform E_1^s for distilled water at T=21 degrees C.

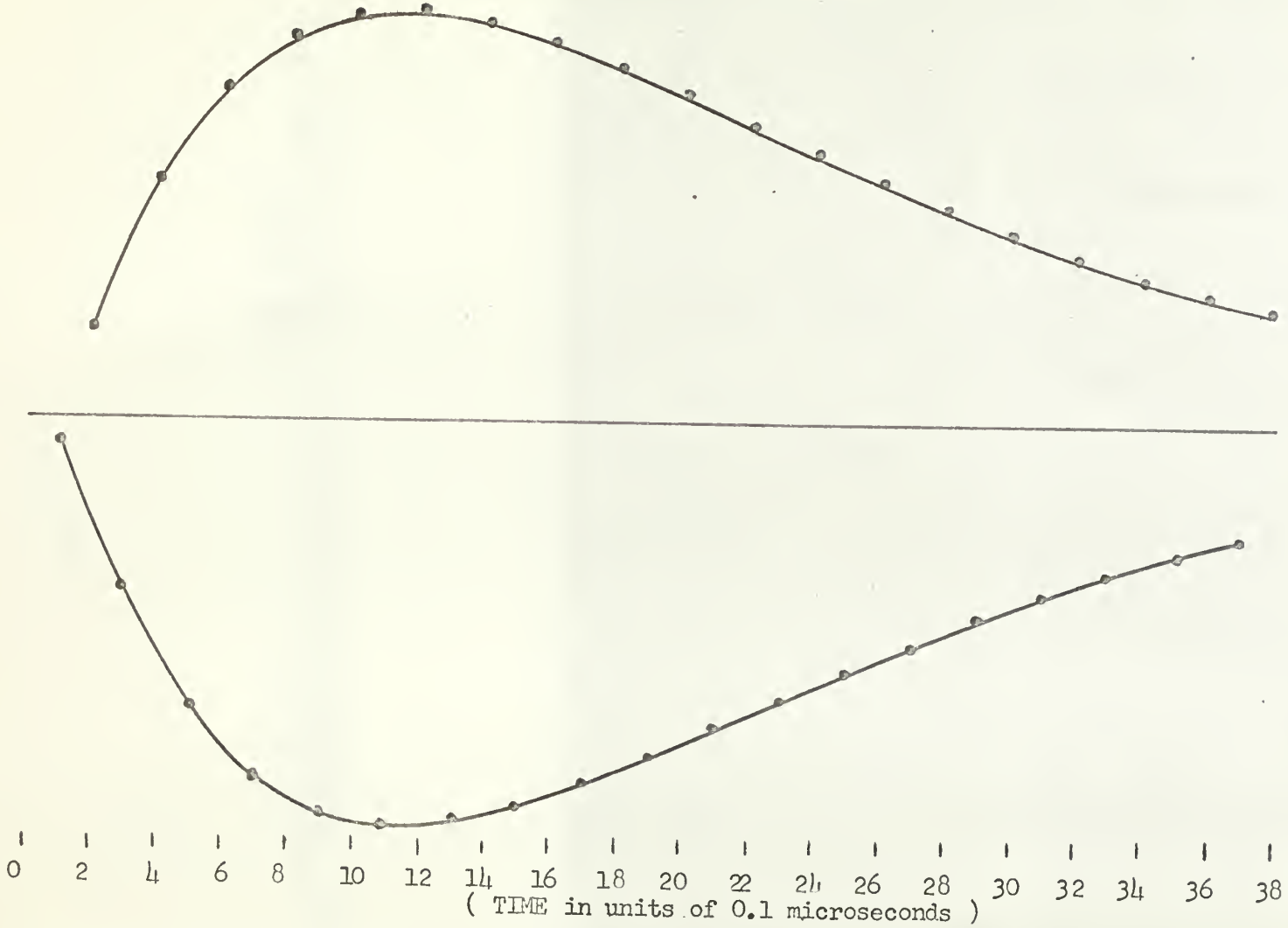


Figure 15. E_r° for Distilled Water. T=21°C (Z=1.482312 X 10^6 rayls)
Solid curve represents theoretical envelope.
Dots represent normalized experimental data.

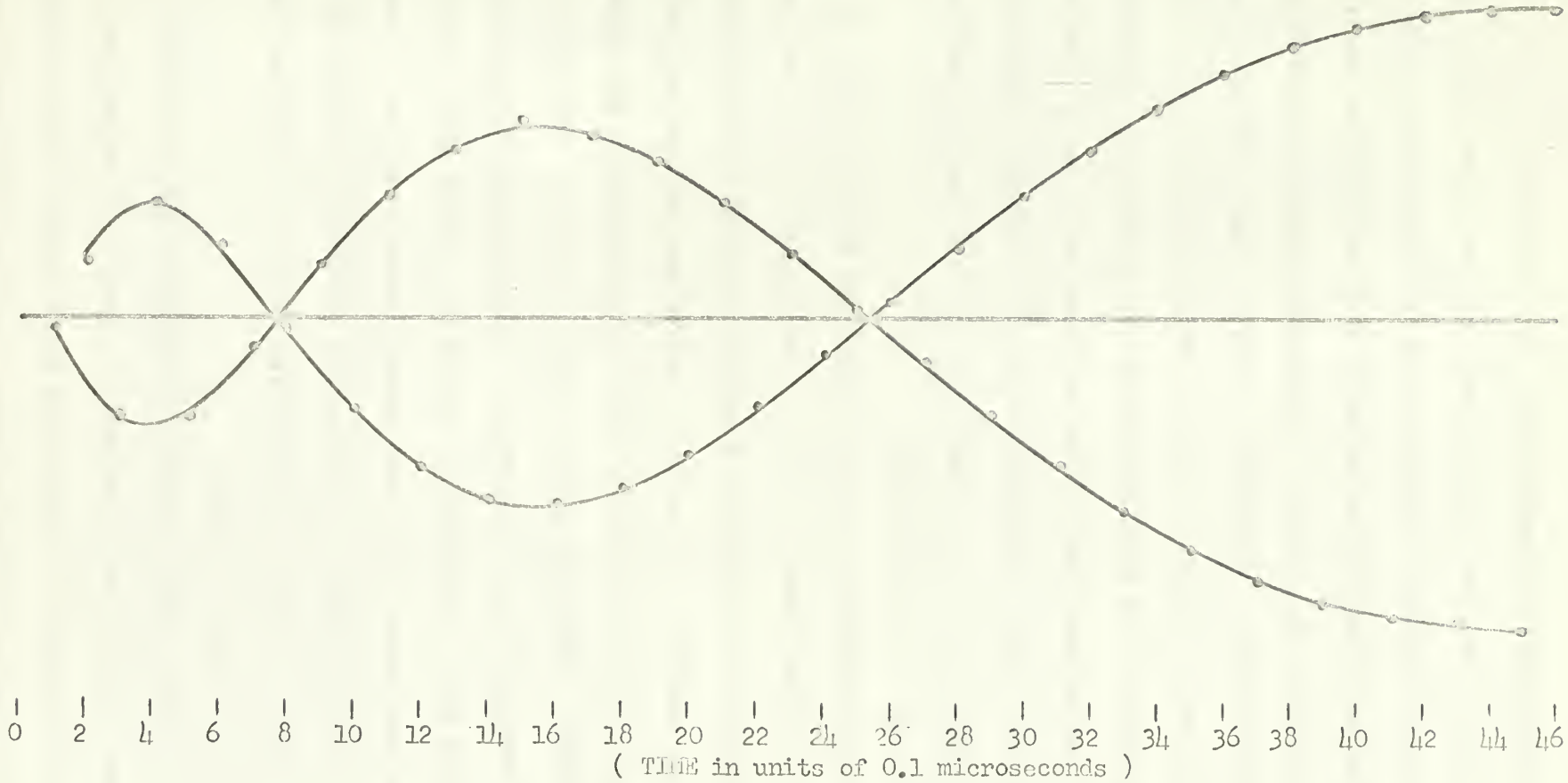


Figure 16. E_1^2 for Distilled Water. T=21° C (Z=1.482312 X 10^6 rayls)
Solid curve represents theoretical envelope.
Dots represent normalized experimental data.

It was observed that each actual negative pulse fell farther from the calculated curve than did each positive pulse. This suggested that the dc reference voltage on the oscilloscope was slightly biased; further investigation indicated that the wide band amplifier was not symmetric, ie., positive pulses were amplified slightly more than negative pulses. Consequently, just the amplitudes of the positive pulses were recorded. Since the maximum reading error of the voltage pulses was the error associated with placing the dc reference on top of the voltage trace on the oscilloscope, it was a fixed error for all pulses. This fixed positioning error therefore, causes much larger maximum possible percentage errors for the smaller amplitude pulses than for the larger pulses.

With the exception of the salt water and distilled water at 25.0^{o}C, the fluids listed in Table II were tested in this analysis. The absorption was so great for glycerol that only the first output voltage was received. The acoustic bond between mercury and quartz was so poor that only the first output voltage waveform was assumed to be reliable. These are shown in Figs. 22 and 23. The results for pentane, tert-butyl chloride, acetone, turpentine and nitro-benzine are shown in Figs. 17 through 21. As in the case of water, the individual voltage pulses within each waveform were normalized to the maximum positive voltage to indicate the correlation in waveform shapes between the actual and calculated values. As mentioned above, only positive values are shown.

In all cases, prior to testing the known fluid, the crystals were cleaned with potassium hydroxide to remove the vacuum grease that may have coated the crystal from prior testing. This, however, was the only special precaution taken. The test fluids were taken

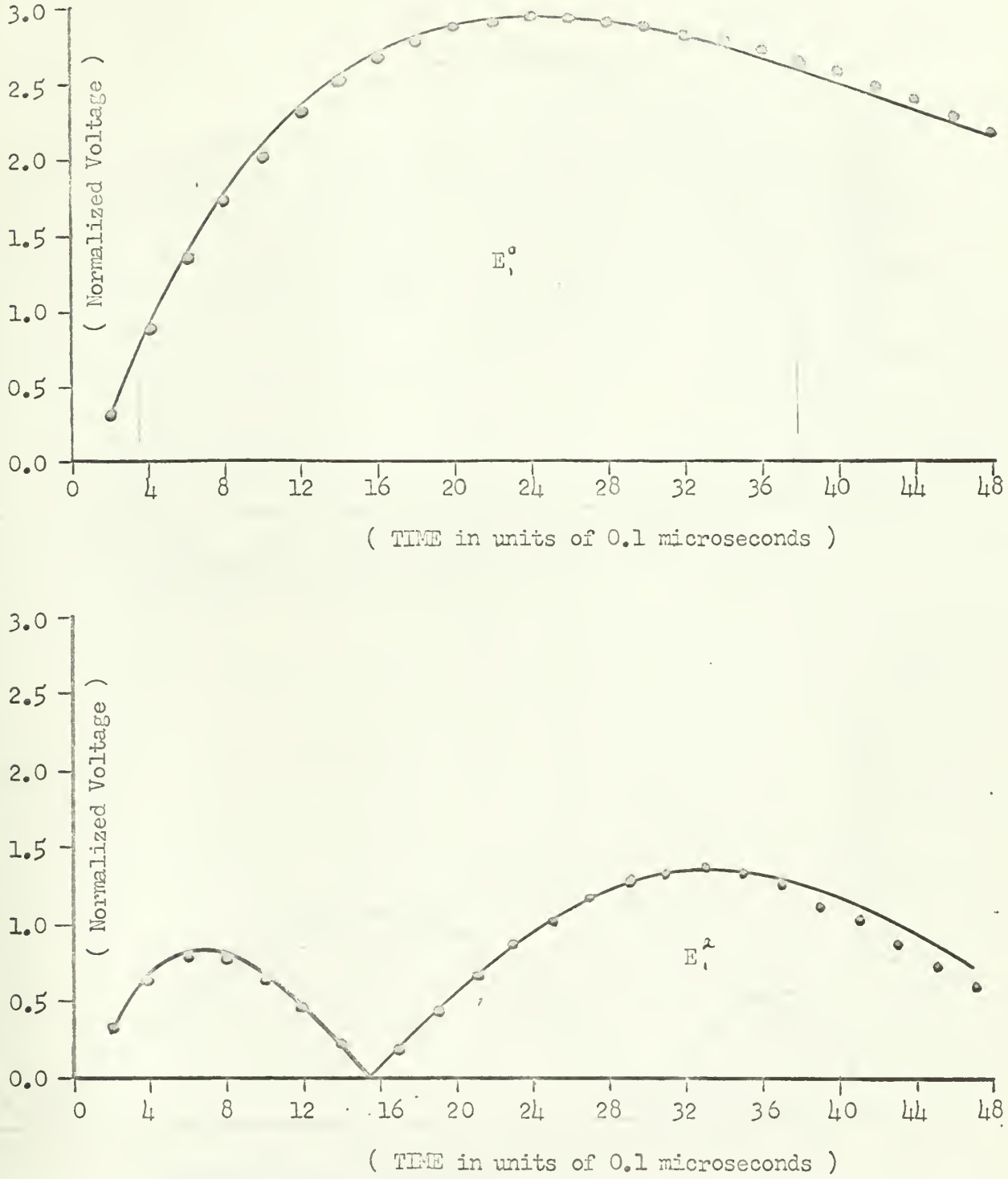


Figure 17. E_1° and E_1^2 for Pentane. ($Z=0.66 \times 10^6$ rayls)
Solid curve represents theoretical envelope.
Dots represent normalized experimental data.

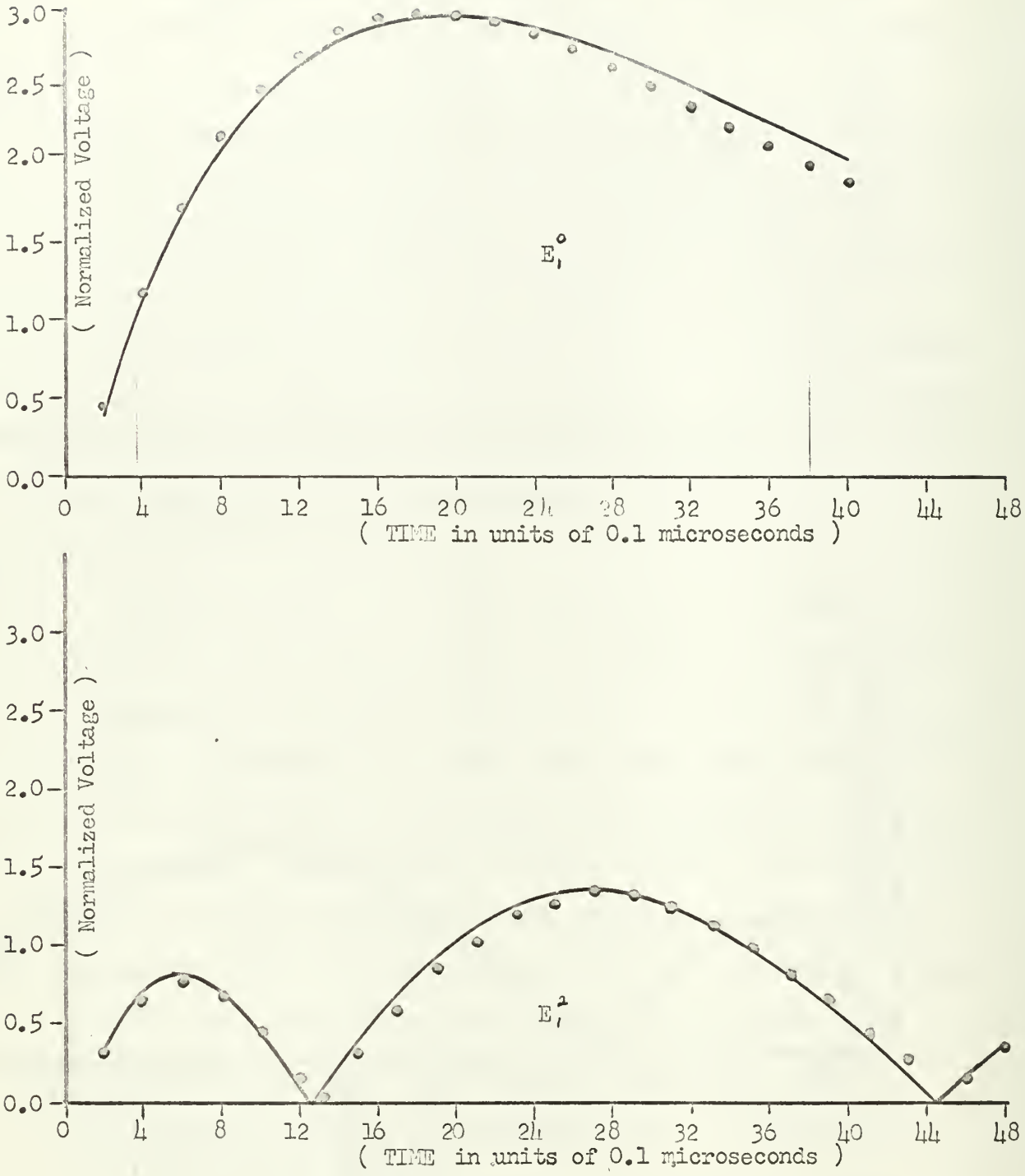


Figure 18. E_1^0 and E_1^2 for Tert-Butyl Chloride. ($Z=0.827 \times 10^6$ rayls)
Solid curve represents theoretical envelope.
Dots represent normalized experimental data.

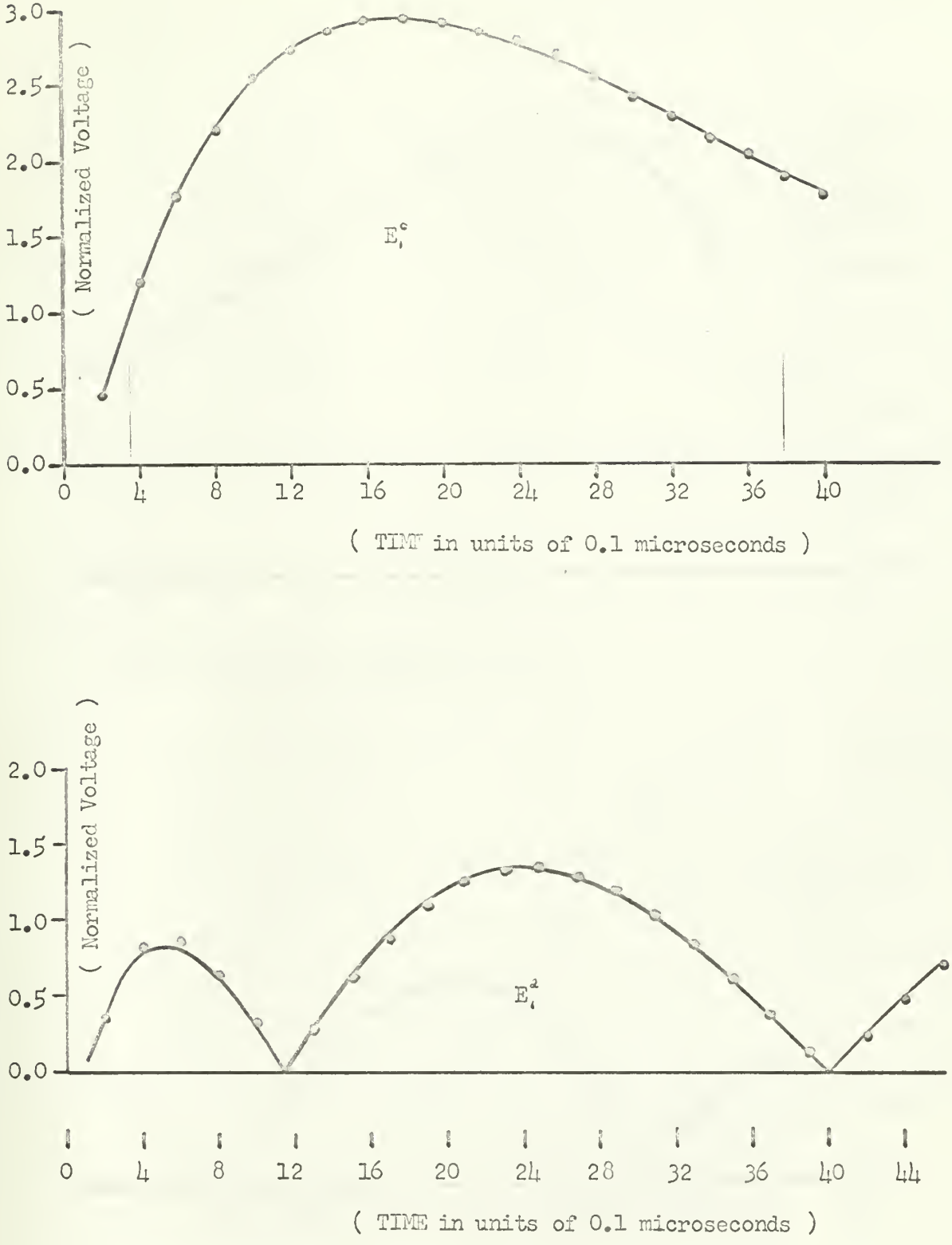


Figure 19. E_i° and E_i^2 for Acetone. ($Z=0.925 \times 10^6$ rayls)
Solid curve represents theoretical envelope.
Dots represent normalized experimental data.

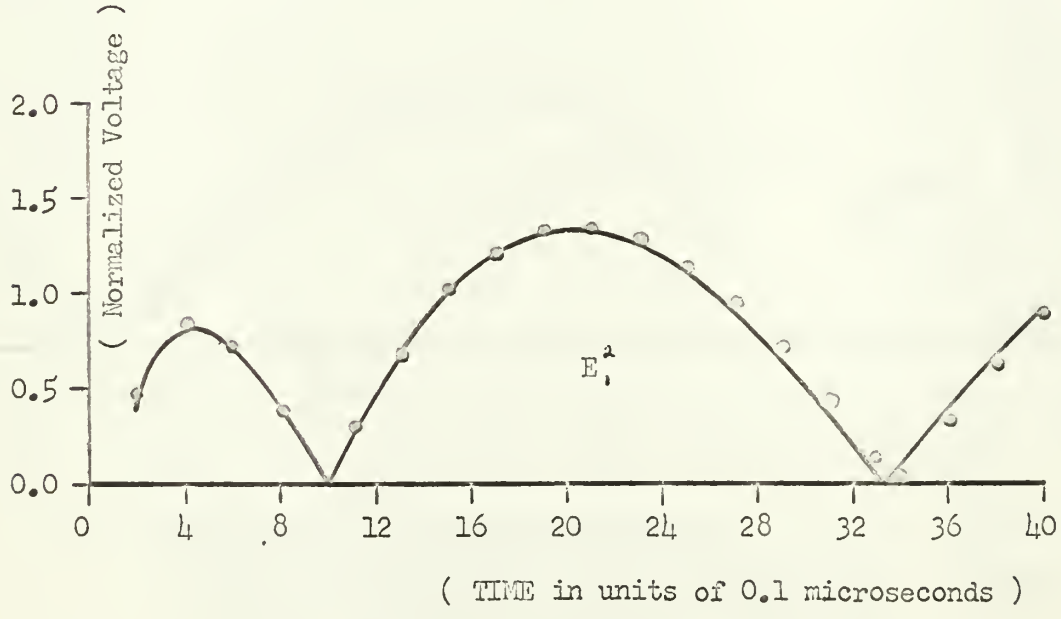


Figure 20. E_1° and E_1^2 for Turpentine. ($Z=1.11 \times 10^6$ rayls)
Solid curve represents theoretical envelope.
Dots represent normalized experimental data.

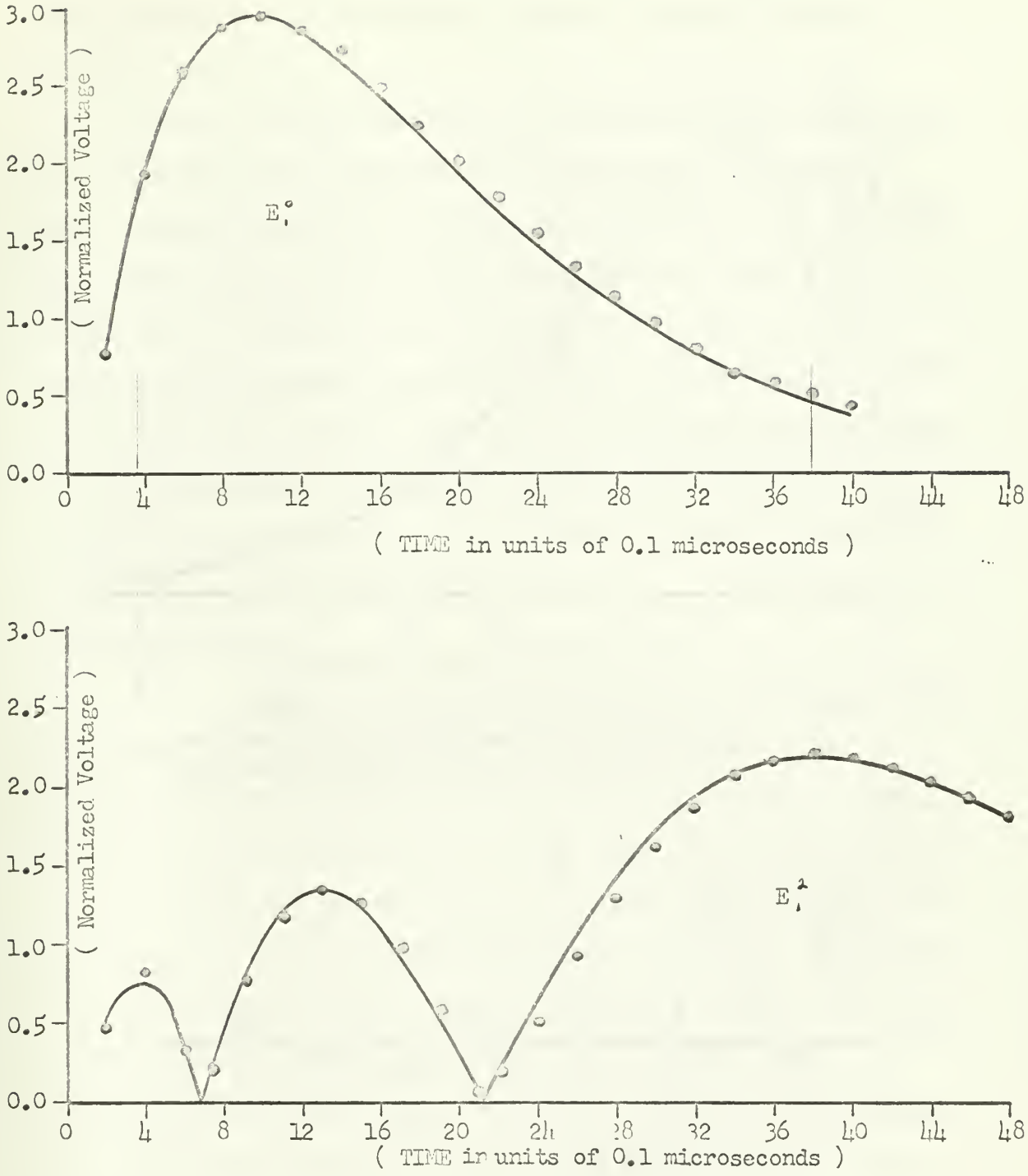


Figure 21. E_1° and E_1^2 for Nitro Benzine. ($Z=1.788 \times 10^6$ rayls)
Solid curve represents theoretical envelope.
Dots represent normalized experimental data.

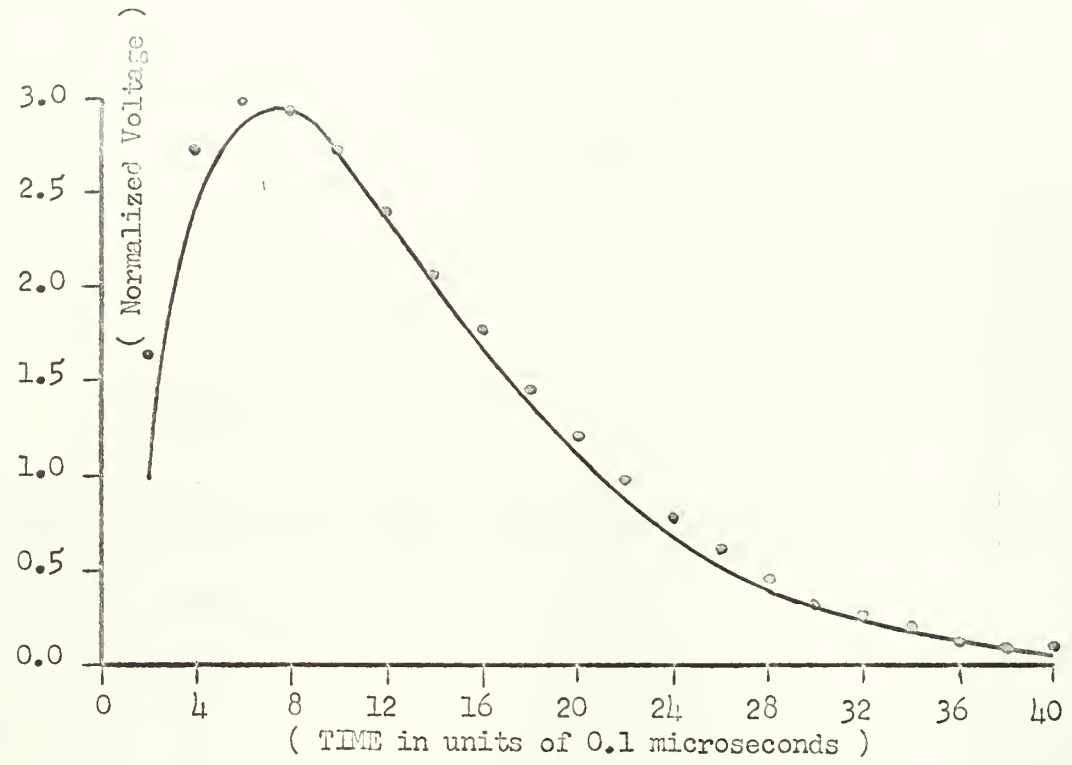


Figure 22. E_1° for Glycerol. ($Z=2.50 \times 10^6$ rayls.)
Solid curve represents theoretical envelope.
Dots represent normalized experimental data.

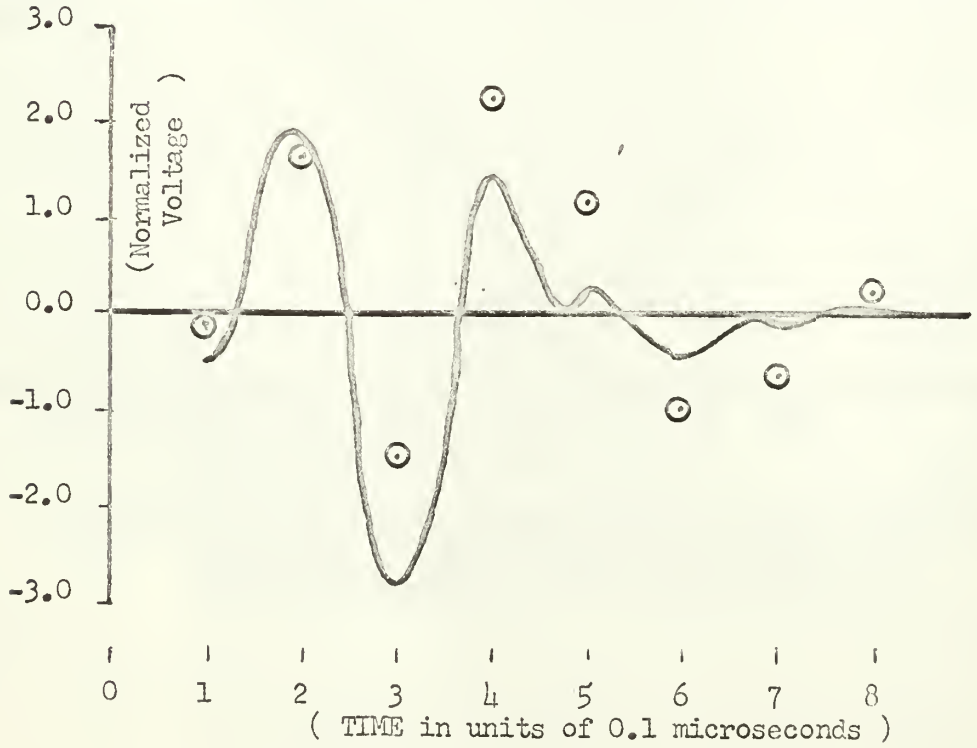


Figure 23. E_1° for Mercury. ($Z=19.7 \times 10^6$ rayls.)
Solid curve represents theoretical envelope.
Dots represent normalized experimental data.

from laboratory supplies and were assumed to have the values of ρc listed in Table II.

With the exception of mercury, no difficulties were encountered in obtaining results. Because of the difficulties in obtaining a good acoustic bond between mercury and quartz however, special problems did develop. The unpolished quartz crystals enabled some trapped air to exist between the mercury and the crystal. It was thought that coating the crystal with a thin film of fluid, with an impedance closer to mercury than to air, would fill the spaces in the face of the crystal, permitting a reasonable bond. Liquid soap was finally used as the coating fluid and adequate results then were obtained and are shown in Fig. 23.

6. Error Analysis

With the exception of glycerol and mercury, the first two output voltages E_1^o and E_1^a are shown for the fluids tested in Figs. 17 through 21. Only the first two are shown because it is felt that these two, and in particular the second, supply sufficient information to confirm the theory and to enable a definite correlation criterion between acoustic impedance and output waveforms. In addition, the assumptions previously mentioned of lossless crystals and fluids, become less valid as the pulses continue to propogate. A few of these neglected losses are; losses within the crystal, absorption in the fluid, beam spreading within the fluid and improper geometrical alignment of crystals and the fluid chamber.

In general, the assumption of lossless crystals will remain valid for all pulses, since the fractional loss within the crystal of each pulse should remain the same for all pulses, regardless of amplitude.[12] Beam spreading should be at a minimum for a perfectly

guided wave, that is, with the plated crystal diameter being exactly equal to the diameter of the test cavity. However, when crystals of smaller plating diameter are used, spreading losses can become significant, [3] eventually causing the amplitude of each pulse to decrease below the predicted values. If the crystals are not parallel, the wave front will strike the crystal at an angle slightly different from the normal, causing a decrease in amplitude. As previously mentioned, care was taken in the equipment design and construction to minimize this error.

Although the absolute values of the individual pulses have not been considered in this study, a knowledge of the ability to predict their values is necessary as a further confirmation of the theory: Equation 30 can be expressed as

$$E = -\frac{h_1 R C_0}{Z} \frac{T_1}{M_1} F_{(p)} \tag{31}$$

where $F_{(p)}$ is the infinite series of pressure terms. Equation 12, however, enables us to write the pressures as a function of applied voltages. Therefore Eq. 31 becomes

$$E = -\frac{h_1 R C_0}{Z} \frac{T_1}{M_1} F(a v_{e1}),$$
$$\text{or} \quad E = -\frac{h_1 R C_0}{Z} a \frac{T_1}{M_1} F(v), \tag{32}$$

and $\frac{T_1}{M_1} F(v)$ is what the program listed in Appendix I is designed to compute. By defining

$$X = \frac{T_1}{M_1} F(v),$$

Eq. 31 may be expressed as

$$E = -\frac{h_1 R C_0}{Z} a X \tag{33}$$

from Eq. 4, $a = \epsilon h_1 / 4\pi d$, therefore

$$E = -\frac{h_1^2 R C_0 \epsilon}{4\pi d Z} X \tag{34}$$

The rms uncertainty in E may therefore be expressed as

$$\frac{\delta E}{E} = \left[2\left(\frac{\delta \rho}{\rho}\right)^2 + \left(\frac{\delta R}{R}\right)^2 + \left(\frac{\delta \epsilon}{\epsilon}\right)^2 + \left(\frac{\delta d}{d}\right)^2 + \left(\frac{\delta Z}{Z}\right)^2 + \left(\frac{\delta X}{X}\right)^2\right]^{1/2} \qquad (35)$$

where $\frac{\delta f}{f}$ designates the uncertainty in the quantity f.

From repeated calculations using the computer program it can be shown that variations in either Z, Z_1, or Z_2 of up to 10 percent causes an amplitude deviation in X of less than 0.1 percent. However, variations in the applied voltage have a direct bearing on the output voltage and the input voltage is estimated to be accurate to well within 1.0 percent. The overall change in the output voltage due to the error in X is therefore, estimated to be 1.0 percent or less.

From Bechman,[13] h is (43.6 $\pm$0.1) X 10^8 v/m and ϵ is (4.32 $\pm$0.01)ϵ_o farads/m. From Mason,[8] the acoustic impedance of quartz, Z, is (1.52 $\pm$0.01) X 10^6 rayls. The equipment manual listed R as 200 ohms and its accuracy was estimated to be 5.0 percent. The value of C_o was measured as 80 X 10^{-6} farads, with an estimated accuracy of 10.0 percent. d was measured as 0.0226 inches with an accuracy 0.0001 inches. Substitution of the above possible values into Eq. 35 yields a maximum possible error in the prediction of the output voltages of 12 percent. The percentage difference between theoretical and actual voltage for any particular pulse within E_1^o, for distilled water at 21.0 degrees C., is less than 6 percent, well within the maximum possible of 12 percent.

7. Data Evaluation and Conclusions

Examination of the output voltages E_1^o and E_1^a for all of the computed waveforms indicates that the impedance of the fluid in question cannot accurately be determined from the first voltage waveform.

The second voltage E_1^2, however, shows two distinct points of interest. Successive reflections from the faces of the crystals causes an interaction of pulses within the waveform which results in a modulated output voltage. Within the second output voltage waveform E_1^2, there are two points where the envelope of the modulated voltage goes to zero.

When a comparison of the second output waveforms was made for the various test fluids, it was noted that as the acoustic impedance increased, the waveforms appear to be compressed, causing the points of zero amplitude, or points at which the change of phase occurs to be pushed forward in time. The relationship between these phase changes and the impedance of the fluid in the waveguide can be seen in Fig. 24. Figure 24 is a plot of the acoustic impedance as the ordinate, and the time to reach the first and second axis crossing as the abscissa. The ordinate represents the entire range of impedances studied where the axis crossings are discernable. Values of the various impedances used as well as the theoretical and actual values of time for the first and second axis crossing are listed in Table 11.

Figures 25 and 26 are expanded sections of Fig. 24 for the range of impedance of particular interest. The solid curve represents the calculated values and the dots are the measured values for the fluids investigated. The estimated accuracy for the measured time of axis crossings is 0.1 units. In the neighborhood of water, $Z = 1.5 \times 10^6$ rayls, the slope of the curve in Fig. 26 is 0.07×10^6 rayls per unit abscissa. In this area then, the $\pm$ 0.1 estimated error in axis crossing corresponds to 0.9 percent error in acoustic impedance. The error in impedance measurement near 2.5×10^6 rayls

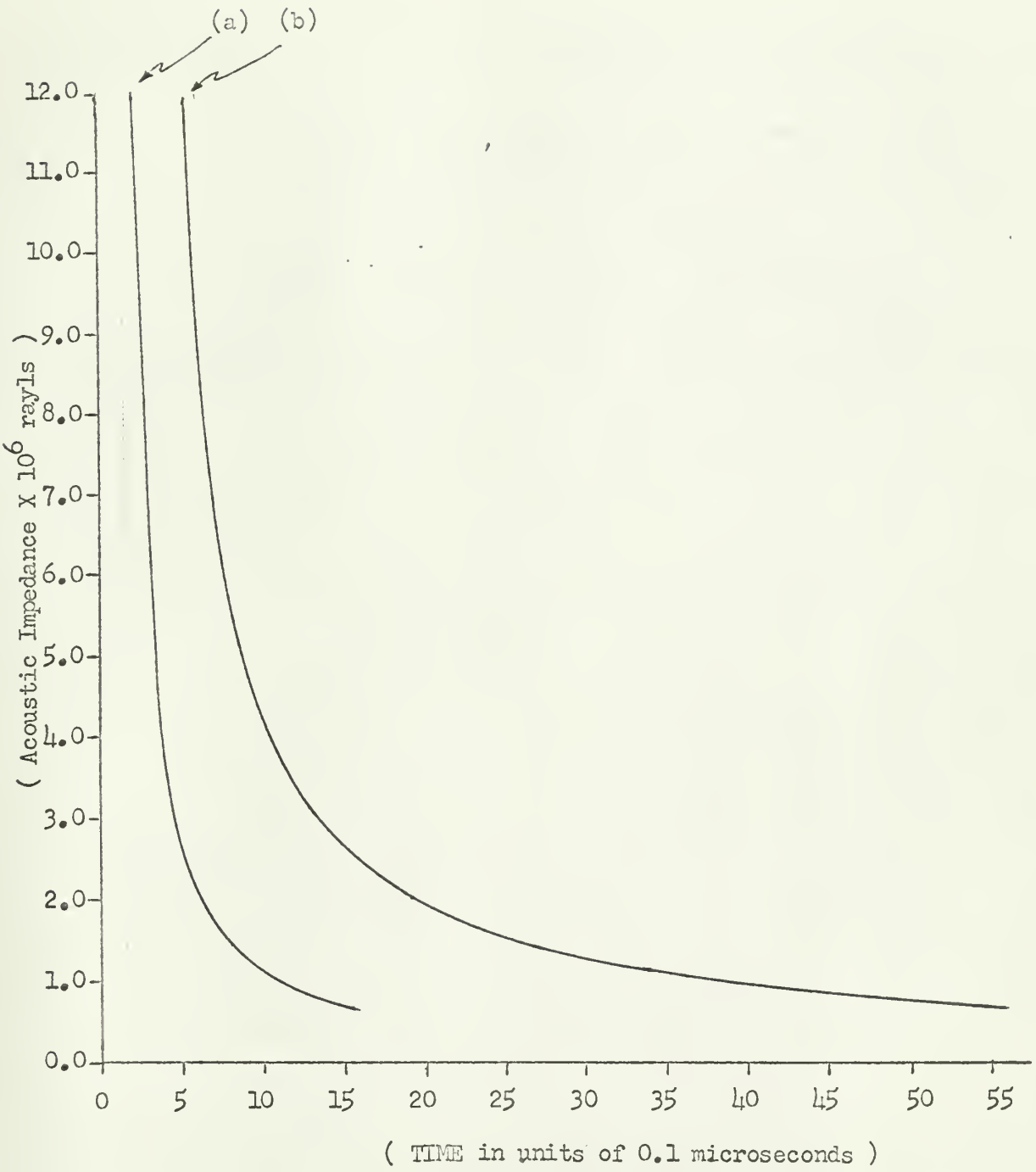
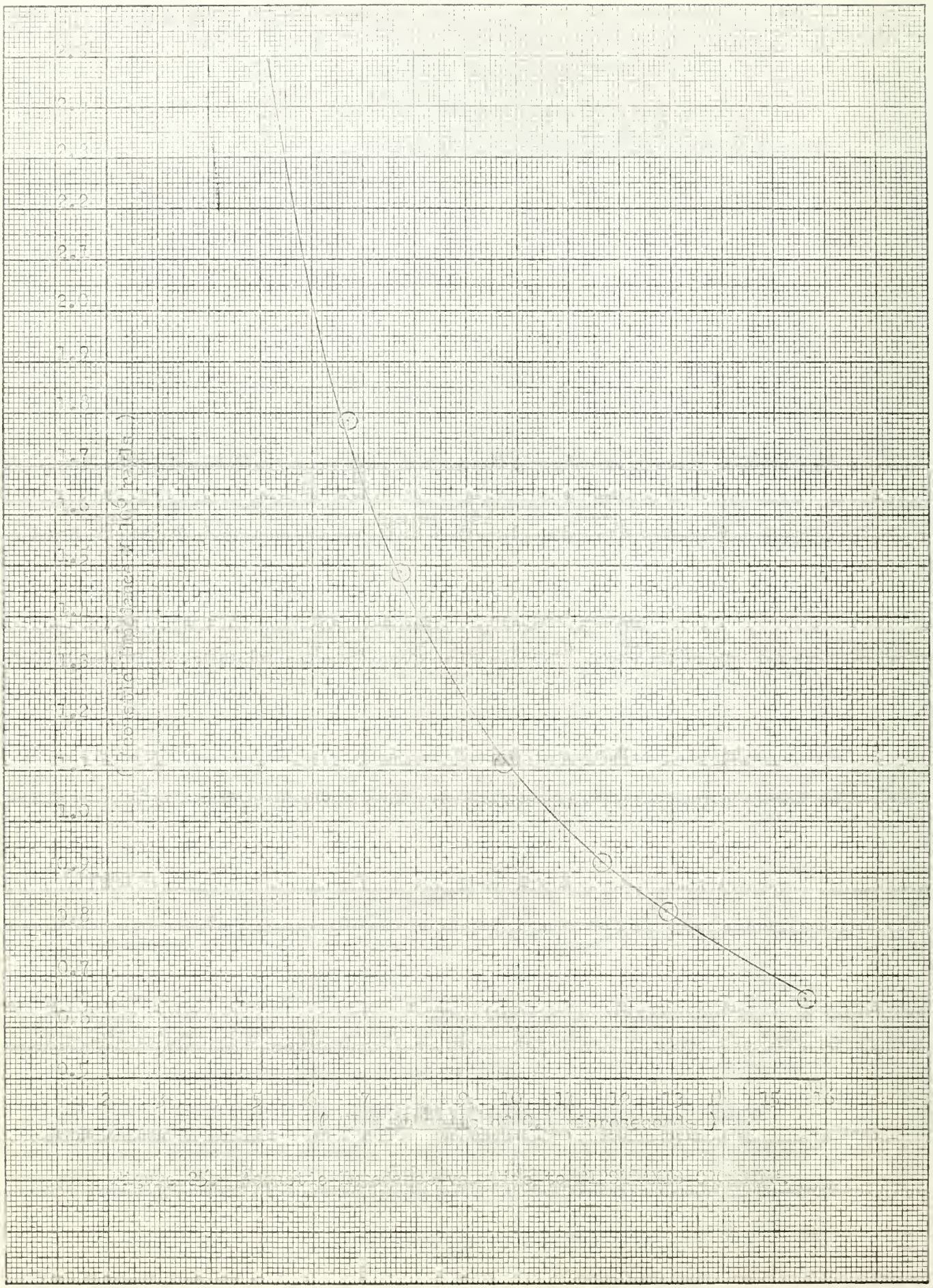


Figure 24. Acoustic Impedance vs. Time to a) First axis crossing.
b) Second axis crossing.



2.50
2.25
2.00
1.75
1.50
1.25
1.00
0.75
0.50
Acoustic Impedance (Rayls)
(Unit is cm/s of 0.1 microseconds)

is estimated to be less than 2.0 percent and when near 0.66 X 10^6 rayls to be less than 0.5 percent. Because of the greater slope of the curve for the first axis crossing, the accuracy of impedance measurement is somewhat less, and for this reason the second axis crossing is recommended for impedance measurements.

The accuracy just mentioned indicates that the method described is not sensitive enough to determine small changes in salinity. Larger changes in salinity, in the neighborhood of 2 to 3 ppt, should be discernable.

Since the most tedious part of the determination of acoustical impedance is measuring all pulses in the area of the axis crossing, and then plotting these to determine the time of the axis crossing, any device that would simplify this would be an asset. If an envelope detector were devised for use with the output voltage waveforms, so that the axis crossing could be directly measured from the oscilloscope, immediate acoustic impedance measurements would be available.

The "carrier frequency" of the output voltage waveforms is the resonance frequency of the piezoelectric crystals used, in this case 5 mc. Since this frequency is within one of the special broadcast bands utilized for radio communications, perhaps the same form of demodulation could be used as an envelope detector.

A "Record and Disclosure of Invention" form has been filed with the Department of the Navy, Office of Naval Research, on this method of impedance measurement for possible Patent Application.

8. Acknowledgements

This work has been supported in part by the U.S. Office of Naval Research, and the U.S. Navy Bureau of Ships. The author would like

to express his appreciation to Asst. Prof. A.B. Coppens for his suggestions and helpful comments, and to Mr. R.C. Moeller and Mr. H.D. Whitfill for their assistance in construction and design of the necessary equipment.

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C      THE FOLLOWING PROGRAM WILL COMPUTE, PRINT AND PLOT THE VOLTAGE
C   OUTPUTS FROM THE RECEIVING CRYSTAL OF AN ACOUSTICAL DELAY LINE WHEN
C   THE TRANSMITTING CRYSTAL IS EXCITED BY AN ARBITRARY DRIVING SIGNAL.
C   ALTHOUGH THE PROGRAM WAS DESIGNED PRIMARILY FOR IMPLUSE SIGNALS, IT
C   WILL WORK EQUALLY WELL FOR CONTINUOUS SUGNALS.
C      THE PROGRAM COMPUTES THE FIRST 13 PRESSURE WAVEFORMS, P10, THROUGH
C   P113, AND THEREFORE THE FIRST 7 VOLTAGES, E10 THROUGH E13. THESE
C   NUMBERS CAN EASILY BE INCREASED BY MODIFYING THE CARDS NUMBERED 50
C   AND 60 AS WELL AS THE DIMENSION STATEMENTS.
C      THE FOLLOWING PROCEDURES SHOULD BE FOLLOWED WHEN UTILIZING THIS
C PROGRAM.
C           1) CARDS 1 THROUGH 4 ARE TO BE USED TO BUILD AN ARRAY, V(N),
C              OF VOLTAGES,EQUALLY SPACED IN TIME. THE UNIT OF TIME BEING
C              ONE SIXTH THE TIME OF FLIGHT IN THE CRYSTAL. THEREFORE,
C              EACH GROUP OF SIX VOLTAGES COMPLETELY FILL THE CRYSTAL.
C           2) THE THREE IMPEDANCES MUST BE SPECIFIED AS FOLLOWS.
C                    5  Z1= IMPEDANCE OF THE FLUID IN THE WAVEGUIDE.
C                    6  Z = IMPEDANCE OF THE CRYSTAL.
C                    7  Z2= IMPEDANCE OF THE BACKING MEDIA.
C           3) THE FIRST AND LAST VOLTAGE TO BE PLOTTED MUST BE SPECIFIED
C              USING CARDS 8 AND 9.
C                    8  LOOK1= THE FIRST VOLTAGE PLOTTED.
C                    9  LOOK2= THE LAST  VOLTAGE PLOTTED.
      DIMENSION V(500),PP(500,13),EE(500,13)
C  THE FOLLOWING 6 CARDS, PLUS ONE DATA CARD PUTS IN THE VOLTAGE FUNCTION
    1 V(1)=1.00
      V(2)=0.00
      DO 3 N=3,500
    3 V(N)=V(N-1)
      CONTINUE
    4 CONTINUE
C  NOTE  V(N) DOES NOT INCLUDE THE CONSTANT A (SEE THEORY)
    5 Z1=1.48231E+06                                          FR T=21
    6 Z= 1.52000E+07
    7 Z2= 4.15000E+02
```

```
    8 LOOK1=1
    9 LOOK2=5
      A1=Z1/Z
      A2=Z2/Z
C   A1 AND A2 IN PROGRAM REPRESENT M1 AND M2 IN THEORY
      T1=(2.0*A1)/(A1+1.0)
      T2=(2.0*A2)/(A2+1.0)
      R1=(A1-1.0)/(A1+1.0)
      R2=(A2-1.0)/(A2+1.0)
      B1=A1/(1.0+A1)
      B2=-1.0/(1.0+A2)
      B3=-1.0/(A1-1.0)
      R1R2=R1*R2
C   COMPUTE THE INITIAL PRESSURE OUTPUT (P10) FROM THE FIRST CRYSTAL
      M=5
      INDEX=1
      DO 11 N=INDEX,M
   11 PP(N,1)=B1*V(N)
      INDEX=INDEX+6
      DO 12 N=INDEX,M
   12 PP(N,1)=PP(N,1)+B2*T1*V(N+1-INDEX)
      IEXP=0
   13 IEXP=IEXP+1
      INDEX=INDEX+6
      DO 14 N=INDEX,M
   14 PP(N,1)=PP(N,1)+B3*T1*V(N+1-INDEX)*(R1R2)**IEXP
      INDEX=INDEX+6
      DO 15 N=INDEX,M
   15 PP(N,1)=PP(N,1)+B2*T1*V(N+1-INDEX)*(R1R2)**IEXP
      IF(INDEX + 12 - 500) 13,21,21
   21 CONTINUE
      C1=-T1/A1
C   NOTE C1 DOES NOT INCLUDE D11,R, OR C0 IN THE NUMERATOR OR Z IN THE
C   DENOMINATOR (SEE THEORY)
      C2=-C1*T2/A2
      C3=-(C1*T1)/(A1*R1)
C   STATEMENTS 50 THROUGH 59 WILL COMPUTE THE REMAINING PRESSURE PACKETS
      LOCK=2*(LOOK2)-1
```

```
   50 DO 59 NN=2,LOCK
      INDEX=1
      M=5
      IEXP=0
      DO 51 N=INDEX,M
   51 PP(N,NN)=-R1*PP(N,NN-1)
   52 INDEX=INDEX+12
      DO 53 N=INDEX,M
   53 PP(N,NN)=PP(N,NN)+T1**2*(R2/A1)*PP(N+1-INDEX,NN-1)*(R1R2)**IEXP
      IEXP=IEXP+1
      IF(INDEX+12-500) 52,59,59
   59 CONTINUE
C  STATEMENTS 60 THROUGH 69 WILL COMPUTE THE OUTPUT VOLTAGE PACKETS
   60 DO 69 NN=1,LOCK,2
      INDEX=1
      M=5
      DO 61 N=INDEX,M
   61 EE(N,NN)=C1* PP(N,NN)
      INDEX=INDEX + 6
      DO 62 N=INDEX,M
   62 EE(N,NN)=EE(N,NN) + C2*PP(N+1-INDEX,NN)
      IEXP=0
   66 IEXP=IEXP+1
      INDEX=INDEX+6
      DO 63 N=INDEX,M
   63 EE(N,NN)=EE(N,NN)+C3*PP(N+1-INDEX,NN)*(R1R2)**IEXP
      INDEX=INDEX+6
      DO 64 N=INDEX,M
   64 EE(N,NN)=EE(N,NN)+C2*PP(N+1-INDEX,NN)*(R1R2)**IEXP
      IF (INDEX + 12 - 500) 66,69,69
   69 CONTINUE
C  STATEMENTS 73 THROUGH 76 WILL PRINT OUT THE VOLTAGES VALUES OF THE
C  SEVEN VOLTAGE PACKETS COMPUTED.
   73 PRINT 74
   74 FORMAT(1H ///)
      PRINT 75
  750FORMAT(112H  N        E10(N)          E12(N)          E14(N)
     1   E16(N)          E18(N)          E110(N)         E112(N))
```

```
      PRINT 76,(N,EE(N,1),EE(N,3),EE(N,5),EE(N,7),EE(N,9),EE(N,11),EE(N,
     113),N=1,500)
   76 FORMAT(1H(I3,1H)E15.8,E15.8,E15.8,E15.8,E15.8,E15.8,E15.8)
C  STATEMENTS 80 THROUGH 81 WILL PLOT THOSE VOLTAGES SPECIFIED IN
C  CARDS 8 AND 9. VOLTAGE IS PLOTTED AGAINST TIME, THE INCREMENT OF TIME
C  BEING ONE SIXTH THE VALUE OF THE THICKNESS OF THE CRYSTAL DEVIDED BY
C  THE SPEED OF SOUND IN THE CRYSTAL
   80 DIMENSION Y(500),X(500),LABEL(7),IT(12)
      J=0
      LABEL(1)=8HE10 VS.
      LABEL(2)=8HE12 VS.
      LABEL(3)=8HE14,VS.
      LABEL(4)=8HE16,VS.
      LABEL(5)=8HE18,VS.
      LABEL(6)=8HE110,VS.
      LABEL(7)=8HE112,VS.
      DO 81 K=1,12
   81 IT(K)=8H
      IT(2)=8HTIME (CA
      IT(3)=8HLCULATED
      IT(4)=8H)
      IT(5)=8HSHEEHAN
      IT(6)=8H(0442)
      IT(7)=8HFRESH WA
      IT(8)=8HTER Z=1.
      IT(9)=8H4823E+06                                          FR T=21
      JK=1
      DO 82 J=1,500
   82 X(J)=J+20
      DO 84 KK=LOOK1,LOOK2
      LAB=LABEL(KK)
      DO 83 N=1,500
   83 Y(N)=EE(N,JK)
      IT(1)=LAB
      JK=JK+2
   84 CALL DRAW(500,X,Y,0,0,LAB,IT,60.,1.,3,0,2,2,9,6,0,LAST)
      END
     END
```

APPENDIX II

Voltage Pulses within E , for Distilled Water at 21°C.

	CALCULATED AMPLITUDES (Arbitrary Units)	CALCULATED VOLTAGES	MEASURED VOLTAGES
1	-0.1619 v.	-0.341 mv.	-0.311 mv.
2	+0.6477	+1.370	+1.283
3	-1.2377	-2.610	-2.472
4	+1.7127	+3.612	+3.470
5	-2.0879	-4.403	-4.186
6	+2.3786	+5.016	+4.799
7	-2.5967	-5.476	-5.179
8	+2.7537	+5.808	+5.556
9	-2.8586	-6.029	-5.706
10	+2.9203	+6.159	+5.864
11	-2.9454	-6.212	-5.854
12	+2.9406	+6.202	+5.932
13	-2.9110	-6.139	-5.795
14	+2.8615	+6.035	+5.749
15	-2.7958	-5.896	-5.562
16	+2.7175	+5.731	+5.484
17	-2.6295	-5.546	-5.255
18	+2.5344	+5.345	+5.103
19	-2.4340	-5.133	-4.871
20	+2.3304	+4.915	+4.731
21	-2.2250	-4.693	-4.455
22	+2.1189	+4.469	+4.292
23	-2.0133	-4.246	-4.034
24	+1.9090	+4.026	+3.899
25	-1.8066	-3.810	-3.640
26	+1.7067	+3.599	+3.509
27	-1.6098	-3.395	-3.257
28	+1.5161	+3.197	+3.112
29	-1.4258	-3.007	-2.868
30	+1.3392	+2.824	+2.729
31	-1.2564	-2.650	-2.525
32	+1.1774	+2.483	+2.405
33	-1.1022	-2.325	-2.198
34	+1.0308	+2.174	+2.118
35	-0.9631	-2.031	-1.937
36	+0.8991	+1.896	+1.876
37	-0.8386	-1.769	-1.685
38	+0.7816	+1.648	+1.640

APPENDIX III

Voltage Pulses within E , for Distilled Water at 21°C.

	CALCULATED AMPLITUDES (Arbitrary Units)	CALCULATED VOLTAGES	MEASURED VOLTAGES
1	-0.1095	-0.231 mv.	-0.148 mv.
2	+0.4379	+0.924	+0.655
3	-0.7507	-1.583	-1.198
4	+0.8131	+1.715	+1.390
5	-0.6987	-1.474	-1.198
6	+0.4806	+1.014	+0.842
7	-0.2013	-0.425	-0.350
8	-0.0967	-0.204	-0.143
9	+0.3910	+0.825	+0.646
10	-0.6594	-1.391	-1.081
11	+0.8921	+1.881	+1.483
12	-1.0796	-2.277	-1.803
13	+1.2198	+2.573	+2.029
14	-1.3107	-2.764	-2.177
15	+1.3544	+2.856	+2.383
16	-1.3533	-2.854	-2.227
17	+1.3116	+2.766	+2.185
18	-1.2336	-2.602	-2.046
19	+1.1242	+2.371	+1.874
20	-0.9984	-2.106	-1.620
21	+0.8310	+1.753	+1.372
22	-0.6569	-1.385	-1.046
23	+0.4704	+0.992	+0.772
24	-0.2757	-0.582	-0.443
25	+0.0763	+0.161	+0.124
26	+0.1242	+0.262	+0.181
27	-0.3232	-0.682	-0.498
28	+0.5178	+1.092	+0.848
29	-0.7063	-1.490	-1.136
30	+0.8865	+1.870	+1.469
31	-1.0573	-2.230	-1.731
32	+1.2174	+2.567	+2.044
33	-1.3660	-2.881	-2.300
34	+1.5025	+3.169	+2.546
35	-1.6265	-3.430	-2.766
36	+1.7379	+3.665	+2.964
37	-1.8366	-3.873	-3.146
38	+1.9227	+4.055	+3.290
39	-1.9967	-4.211	-3.385
40	+2.0587	+4.342	+3.503
41	-2.1093	-4.449	-3.562
42	+2.1490	+4.532	+3.640
43	-2.1783	-4.594	-3.666
44	+2.1979	+4.635	+3.692
45	-2.2084	-4.658	-3.722
46	+2.2104	+4.662	+3.740
47	-2.2040	-4.648	-3.710
48	+2.1917	+4.622	+3.657

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A method has been developed for measuring the acoustic impedance of fluids in a fluid-filled waveguide terminated at each end by piezoelectric crystals. Output voltage waveforms were computed for the general case of an arbitrary driving voltage. Analysis of these output waveforms, when the driving voltage was an impulse function, indicated significant changes in the voltage envelopes as the acoustic impedance of the fluid within the waveguide was varied. The time of the first and second phase changes in the second received echo were plotted as a function of fluid impedance. Test fluids were analyzed with an impedance range of from 0.66×10^6 rayls to 19.7×10^6 rayls. The experimental results using the time of the second axis crossing or phase change as the test criterion, indicated that the acoustic impedance can be measured with the following accuracies:

a. 0.5 percent in the neighborhood of $Z = 0.66 \times 10^6$ rayls.
b. 0.9 percent in the neighborhood of $Z = 1.50 \times 10^6$ rayls.
c. 2.0 percent in the neighborhood of $Z = 2.50 \times 10^6$ rayls.

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